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MEMORANDUM REPORT NO. 1561
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ATMOSPHERIC TRANSMISSION OF LIGHT FOR CLEAR AIR AND FOG IN THE SPECTRAL REGION 0.35 TO 1.10 MICRONS

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RDT & E Project No. 1M523801A286

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ABERDEEN PROVING GROUND, MARYLAND

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ABSTRACT

Methods are described for estimating the transmission of light by a clear atmosphere for humidities ranging from 0.1×10^{-6} to 100×10^{-6} g/cm^3 and temperatures between $-40^{\circ}C$ and $+60^{\circ}C$ for path lengths between 1000 and 5000 meters. Also, transmissions are given for varying amounts of fog for path lengths up to 200 meters. The paths used are horizontal and near sea level and wavelength intervals of 0.05 micron are used between wavelengths of 0.35 and 1.10 microns.

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INTRODUCTION

The problem of transmission of light through the atmosphere is not a new one, and it has been approached in many ways. The difficulties connected with any of the approaches are due to the fact that the atmosphere is a continually varying medium, not only from place to place, but from time to time over the duration of an experiment as well. For this reason, the easiest approach to a study of some atmospheric properties is to postulate an ideal atmosphere and then modify the results accordingly as the atmosphere deviates from the ideal properties assigned.

TRANSMISSION BY CLEAR AIR

For the problem here, the ideal atmosphere is assigned the following properties: a) The range of interest is horizontal and near sea level so that a constant and specified number of molecules per cubic centimeter may be assigned; b) The only constituents of the atmosphere are molecular gases and water vapor so that molecular absorption and Rayleigh scattering offer the only major contributions to the attenuation; and c) The properties of the atmosphere such as relative humidity and temperature are constant over the entire path length and in time so that each unit volume along the light path will affect the light in the same way as any other and no variation is observed during the time it takes to make an experiment.

The formula for Rayleigh scattering is:

$$\sigma_s = \frac{8\pi^3(n-1)^2 6(1+p)}{3N\lambda^4(6-7p)} \left[3 + \frac{1-p}{1+p} \right] \times 10^5 \text{ km}^{-1}$$

where σ_s is the Rayleigh scattering coefficient, λ is the wavelength of the incident light in centimeters, N is the molecular density per cubic centimeter of air, n is the index of refraction of the air, and p is the polarization defect in air for light scattered at an angle of $\pi/2$, which is about 0.04[1]. When the appropriate substitutions are made, the reduced equation for the ideal atmosphere is:

$$\sigma_s = \frac{353(n-1)^2}{N\lambda^4} \times 10^5 \text{ km}^{-1}$$

This equation is plotted in Figure 1 for dry air and for very moist air using average values of n. As can be seen, there is very little difference between the two curves. This means that the scattering does not correlate with the humidity, or σ_s is virtually independent of the amount of water vapor in the air, particularly for the longer wavelengths.

The next step is the determination of the absorption coefficient. To do this, it is first necessary to define the amount of precipitable water vapor in the light path. This is the depth of water which can be condensed on a base with a cross sectional area of one square centimeter if all the water vapor is removed from a straight tube which is one square centimeter in cross sectional area traversing the line of sight between the light source and the observer. It is now easy to compute the humidity from the precipitable water vapor and the range. This is shown in Figure 2. This provides all the physical data that is needed to determine the amount of light absorbed by water vapor along the line of sight.

Larmore[2] tabulates the atmospheric transmission as a function of the precipitable water vapor for wavelength intervals of 0.1 micron for pure absorption throughout the wavelengths of interest in this report. To do this, he uses an error function absorption law derived by Elsasser[3] which states:

$$T = 1 - \mathrm{erf}\left[\frac{\beta}{2}(\pi w)^{1/2}\right]$$

where T is the transmission by a line of sight containing w centimeters of precipitable water vapor, and β is the error-function absorption coefficient. The error-function is defined as:

$$\mathrm{erf}\,[x] = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2}\,dt.$$

The data thus obtained were plotted in Figure 3 covering the wavelengths of interest. The transmission shown is the percentage of light transmitted by the given amount of precipitable water vapor for pure absorption in a wavelength interval of 0.05 micron centered at the wavelength given. Since there is negligible absorption of light of these wavelengths by air molecules, the only contributors to the total attenuation are Rayleigh scattering and water vapor absorption. Thus, the transmission can be described by

$$T = e^{-(\sigma_a+\sigma_s)R}$$

It should be kept in mind that σ_a is not equal to the β already described. In fact it is range dependent and is used only as a convenient parameter for determining the total transmission. σ_a is defined as $T_a = e^{-R\sigma_a}$ where T_a is the transmission by a pure absorbing medium as given in Figure 3. If a value of R is now assigned, the transmission can be tabulated as a function of R and the humidity.

This was done and the results are plotted in Figures 4-19 for various wavelengths. In addition, Figures 20 and 21 are added for convenience in converting the temperature and relative humidity to absolute humidity. Thus, for the ideal atmosphere, the only equipment necessary for the determination of the transmission over a specified range are a thermometer and a device for measuring relative humidity. It should be noted that this information only gives the transmission but gives no hint as to whether or not the source can be detected. This would depend on a variety of factors such as the brightness of the light source, the ambient light level, and the sensitivity of the detector. A further note should be added to the effect that the atmosphere is likely to approach the ideal only if the relative humidity is less than 70%. If it is greater than this, and if there are nuclei for condensation present, the water vapor is likely to condense and droplets can form, giving rise to haze or fog for which Mie scattering must be taken into account[4]. Thus, the values given in this section provide only an upper limit for the transmission, and will be valid only if no haze, fog, dust, etc., are present along the light path.

In a sample procedure, the following steps would be taken to determine the transmission. First the temperature and relative humidity are determined with the appropriate equipment and Figures 20 and 21 are used to find the absolute humidity. The appropriate graph is then found for the wavelength interval of interest (Figures 4-19). Taking care to use only that portion of the graph to the left of the appropriate temperature, the humidity and the desired range are combined to find the percentage of light transmitted in a wavelength interval of 0.05 microns centered at the wavelength given.

If the humidity found is located to the right of the environmental temperature, corresponding to a relative humidity of 70%, (Figures 4-19) or if there are other reasons to suspect that haze or fog is present, the atmosphere is likely to depart widely from the ideal atmosphere we have been considering. A new model must now be considered to determine transmissions under these conditions. Fog is easier to account for than haze so it will be considered first.

TRANSMISSION BY FOG

Even in the most stable of fogs, the frequency distribution of the droplet radii and the number of droplets per cubic centimeter are constantly changing. Thus it is necessary to postulate an ideal fog containing a constant number of droplets per cubic centimeter and a constant number of droplets of any radius per cubic centimeter throughout the duration of the experiment. An important source of error in the cases of transmission by a fog, is the lack of adequate information on the actual radius distributions of the fog droplets. Most methods of droplet capture tend to slight the presence of small droplets (less than 2 microns radius) and often large droplets as well. With these limitations in mind, the radii distributions given by Arnulf and Bricard[5] are excellent for the purposes of this report. The fog radii distribution given was tested by the method outlined below and some reasonable values were obtained.

A spherical droplet of radius r being illuminated by a monochromatic plane wave with an intensity of unity so that the transmission will be fractional, diffuses the light in a portion of the wave front equal in area to $\pi r^2 K_r$ where K_r is the scattering area ratio which is a single valued function of $\alpha = 2\pi r/\lambda$. This function, ignoring the fine structure, is shown in Figure 22. The original curve is given by Houghton and Chalker[6]. The contributions to σ by droplets having radii between r and r + Δr is then $\Delta\sigma_r = \pi r^2 n_r K_r$ where n_r is the number of droplets per cubic centimeter with radii between r and r + Δr. The Mie scattering coefficient is now given by:

$$\sigma_m = \pi \sum_{r=o}^{\infty} n_r \, r^2 \, K_r$$

To facilitate the computation, the following procedure was used. First, values of α and K_r were determined for values of r in 0.5 micron steps from 1.5 to 15 microns and for values of λ in 0.05 micron steps from 0.35 to 1.10 microns and values of $K_r r^2$ found for each value of K_r. Then using the radius distributions of Arnulf and Bricard, n_r was determined and was normalized to the desired total number of droplets per cubic centimeter maintaining a constant radii distribution by letting

$$N = k \sum_{r=1.5\mu}^{15\mu} n_r$$

so that kn_r is the new number of droplets per cubic centimeter with radii between r and r + Δr. Admittedly this is not a rigorous step since increasing the value of N will mean increasing the interaction of the droplets so that the result will be a shift in the peak of the radii distribution function so that the average is for a greater radius of the droplet. Due to the oscillatory nature of K_r, the average values of K_r are likely to be changed very little. Most of the change will appear in $n_r r^2$, and since the average value of r increases while the average value of n_r decreases, and since we are not looking for considerable accuracy due to limited accuracy on other parts of the problem, the validity of this step will be considered adequate for our purposes.

N was then set equal to 20, 40, 80, 160, 320, and 600 droplets per cubic centimeter, and a value of n_r was found for each N and each r. Then for each value of N,

$$\sigma_m = \pi \sum_{r=1.5\mu}^{15\mu} n_r r^2 K_r \text{ was determined.}$$

Several useful graphs can now be drawn. Figure 23 gives the transmission as a function of range for varying values of N for wavelengths of 0.40 and 1.05 microns which represent the wavelengths of maximum and minimum transmissions and goes to show the near wavelength-independence of Mie scattering when a spread of droplet radii are present. Figure 24 shows the transmission as a function of range for the spread of actual fogs given in Arnulf and Bricard compared to the ideal fog of our consideration denoted by the number of droplets per cubic centimeter. A word should be added as to the effect of water vapor in a fog dominated region. In our clear air situation, it was only rarely that the value of σ rose above 1/km (corresponding to a transmission of 0.367 over 1 kilometer). When this is compared to the fogs of Arnulf and Bricard for which σ varied between the approximate limits of 4.5 and 70/kilometer and since, in general, the lower values of σ_m correspond to the lower values of σ for clear air, it is seen that it is usually valid to neglect the effect of water vapor in the path.

The transmission by haze is a very difficult problem to analyze from any kind of a theoretical approach. In a fog, as we have seen, Rayleigh scattering and molecular absorption may be neglected. In a haze, this is not true. The average droplet radius is lower and thus, due to the loss of small droplets in most droplet counting studies, the radius distributions for hazes are very uncertain and in addition the transmission is very sensitive to small changes in the assumptions regarding the haze droplets. Since there are a significant number of droplets with radii less than the wavelength of the light, a haze is highly wavelength dependent.

VISUAL APPROXIMATIONS

Here and in the case of a fog, a method of approximation exists which will allow a man in the field to make a rough estimate of the attenuation with no equipment except for a map or tape measure. This is by the use of the meteorological range of the atmosphere. This term requires some elaboration since it is derived from a different set of circumstances than those previously considered in this report.

Consider the contrast between an object and its background which is of moderately uniform luminance. The contrast between them can be expressed by the equation:

$$\frac{C_R}{|C_o|} = e^{-\sigma R}$$

where C_o and C_R are the observed contrasts at ranges of 0 and R, σ is the atmospheric attenuation coefficient, and R the distance between the object and the observer. Let an object now be observed which is plainly visible against its background and slowly increase the range until the object fades and disappears from view. Several mechanisms can be responsible for its disappearance; the objects angular size can decrease below the limit for visual detection, the object can be obscured by glare from other sources in the field of view, the atmospheric extinction can reduce the apparent contrast to a value which is below that necessary for the eye to detect, etc. Only the last condition will be considered, since it is the main consideration in a haze or fog. The range at which an object will disappear is obviously dependent on the extinction coefficient, and it is this relationship that is desired. To do this, the approach found in Middleton[7] will be used.

Consider the equation:

$$\frac{C_R}{|C_o|} = e^{-\sigma R}$$

If C_R is set equal to the threshold of brightness-contrast, ϵ, the equation becomes $\epsilon = |C_o| e^{-\sigma V}$ where V is the visual range. It is now necessary to assume values for C_o and ϵ. The case of the object being less luminous than its background will be considered. In this case, $-\epsilon > C_o > -1$. $C_o = -1$ is the case for a black body. On the other hand when C_o increases to $-\epsilon$, the object cannot be seen at any range. It shall also be assumed that the object is dark enough that C_o can be assigned the value of -1 without a great error being introduced. This will be justified later in the report. ϵ is a function of both the background luminance and the angle subtended by the object, and can vary considerably. However, for most representative cases, ϵ can be assigned a value of 0.02 making the new equation: $0.02 = \epsilon^{-\sigma V_2}$ where V_2 is referred to as the meteorological range. For the cases of most interest in this problem, V_2 will differ from V by no more than about 15 percent. V can be approximated by the limiting range for which a sufficiently large black object is barely seen against the horizon sky. Since there is usually no visible horizon sky in a fog, some elaboration on this term is necessary. What is desired is a uniformly luminous background of great enough extent that a contrast between it and the observed object may be measured. Thus, a fog background will serve as well since the attenuation is high enough to eliminate the effects of any irregularity in the object's terrestial background. Assuming that V is equal to V_2 for the case under consideration, we can now use the equation $0.02 = \epsilon^{-\sigma V}$. This reduces to $\sigma = \frac{3.912}{V}$ readily giving a value of σ. Thus, by observing the range of disappearance of a dark colored vehicle or the edge of a forest, the attenuation coefficient, σ, can be readily calculated. Figures 25 and 26 demonstrate the transmission of light for various ranges and visual ranges. A restriction which must be placed on these graphs is that the light source must have a constant intensity across the region of 0.4 to 0.7 microns, the response range of the eye. For any other source profile, a similar set of curves can be drawn, however the source profile must be included by a step integration process normalizing the product of the photopic curve of the eye and the source profile.

ACCURACY LIMITATIONS

A number of approximations have been made in this report, and a discussion of the limits of accuracy to which this report is likely to conform might be helpful. The approximations which are most likely to lead to an erroneous answer are: 1) The selection of a proper droplet density and radius distribution for a fog; 2) The selection of an accurate value for ϵ; and 3) The approximation of C_o by -1. Each of these problems will be discussed in turn. The following discussions use Middleton[7] as a primary reference and the secondary references were taken from it without examining the original papers.

There are a wide range of estimates as to the droplet densities and radius distributions in a fog. Kneusel[8] found that there was a sharp peak in occurance frequency for a radius of 2.2 microns for a valley fog, and a less pronounced peak at about 7 microns for a mountain fog. Houghton and Radford[9] obtained an almost gaussian distribution with a peak at about 18 microns. However, as is explained, their method tends to favor the capture of larger droplets. Brun and Demon[10] found two types of fog, one having a maximum at about 10 microns and the other at a much smaller radius. Hann[11] lists a summary of various observers giving a radius spread of 1-64 microns. The data used in this report were taken entirely fron Arnulf and Bricard[5] and ranged from 1.5 to 15 microns in droplet radius with a maximum frequency around 2-3 microns. This corresponds closely to the valley fog of Kneusel. Even though there is wide variation in conditions between different fogs and even in the same fog at different times and places, it is likely that the radius distribution in a fog is not extremely critical as long as there is a reasonable spread of radii so that the oscillatory nature of the scattering area ratio shows its effect.

The number of droplets per cubic centimeter contributes only to the actual transmission. It has no effect on the wavelength dependence of the light. Houghton and Radford[9] found a value of 1-10 droplets/cm^3. However, as was pointed out, their method tends to favor the capture of large droplets. Since the peak occurrence given here is at a moderately small radius (2-3 microns) it is not surprising that the droplet densities appearing most favorable here would seem too large compared to those of Houghton and Radford. Also, when the wide range of possible conditions are taken into account, it is likely that the results given are reasonable.

The selection of a proper ϵ places a definite limit on the accuracy of this report. The information in Middleton suggests that ϵ can vary widely with visual angle and adaptation luminance, reaching values of 0.1 or even greater, but with a maximum occurance at about 0.03. However, in this range, $\ln \frac{1}{\epsilon}$ is moderately insensitive to reasonable changes in ϵ. If $\epsilon = 0.02$, $V_2\sigma = 3.91$ and if $\epsilon = 0.03$, $V_2 \sigma = 3.51$. Thus it can be concluded that due to the wide range of values which ϵ can assume, an assigned value of 0.02 while perhaps unrealistic, is in popular usage, and that its use will not lead to highly divergent results in most cases.

The substitution of -1 for C_o is a valid step only if the observed object is well chosen. In a fog, since specular reflection of direct sunlight is not a problem, the criterion is that the target's diffuse reflectivity is low. Cohen[12] shows that the diffuse reflectivity of a M48 A-1 tank varies between 2.5% and 5.0%. Middleton[7] estimates that a side view of an extensive pine wood has a luminance factor of 0.04. These would serve very well as black bodies for our purposes, since in a fog there would be no glare produced by reflection of direct sunlight. Middleton also states that a grassy hill may have a luminance factor of greater than 0.2. This, on the other hand, would be a poor object for our purposes.

Alan R Downs

ALAN R. DOWNS

FIG. 1 - RAYLEIGH SCATTERING COEFFICIENT FOR DRY AIR AND VERY MOIST AIR UNDER A CONSTANT PRESSURE.

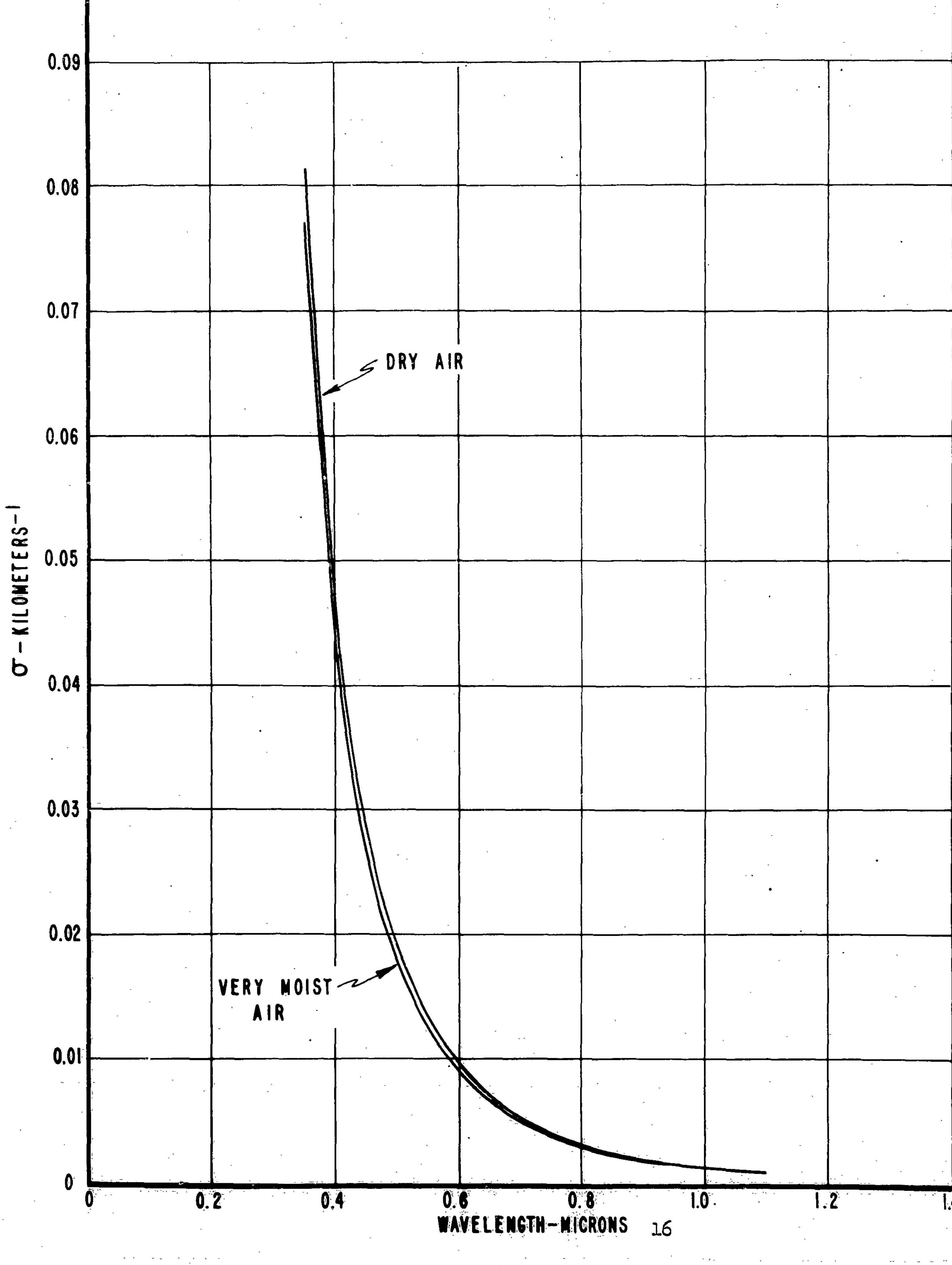


FIG. 2-HUMIDITY AS A FUNCTION OF THE PRECIPITABLE WATER VAPOR ALONG THE LINE OF SIGHT FOR RANGES FROM 1 TO 5 KILOMETERS.

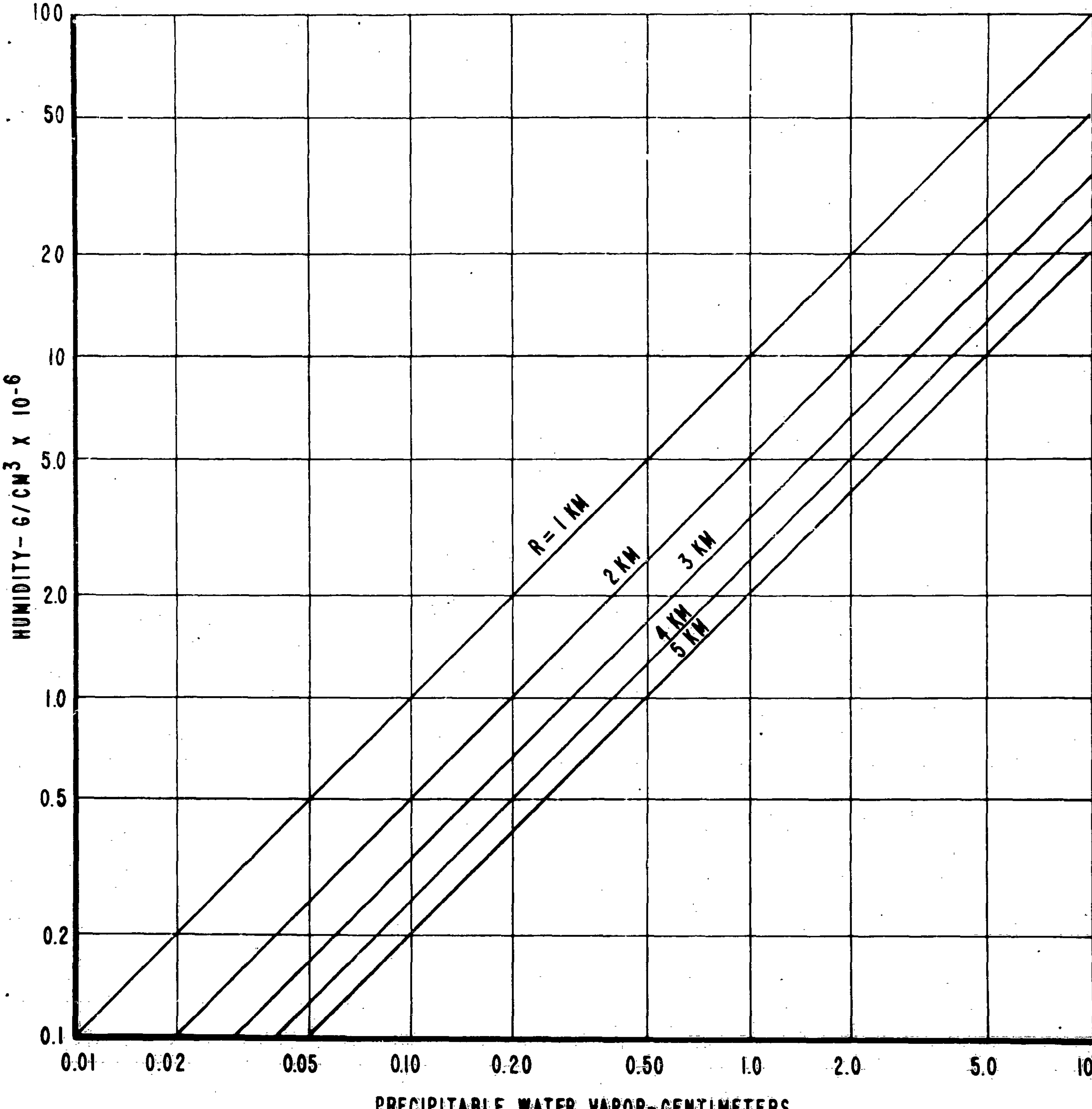


FIG. 3 — TRANSMISSION AS A FUNCTION OF WAVELENGTH WITH PURE ABSORPTION FOR VARYING AMOUNTS OF PRECIPITABLE WATER VAPOR ALONG THE LINE OF SIGHT.

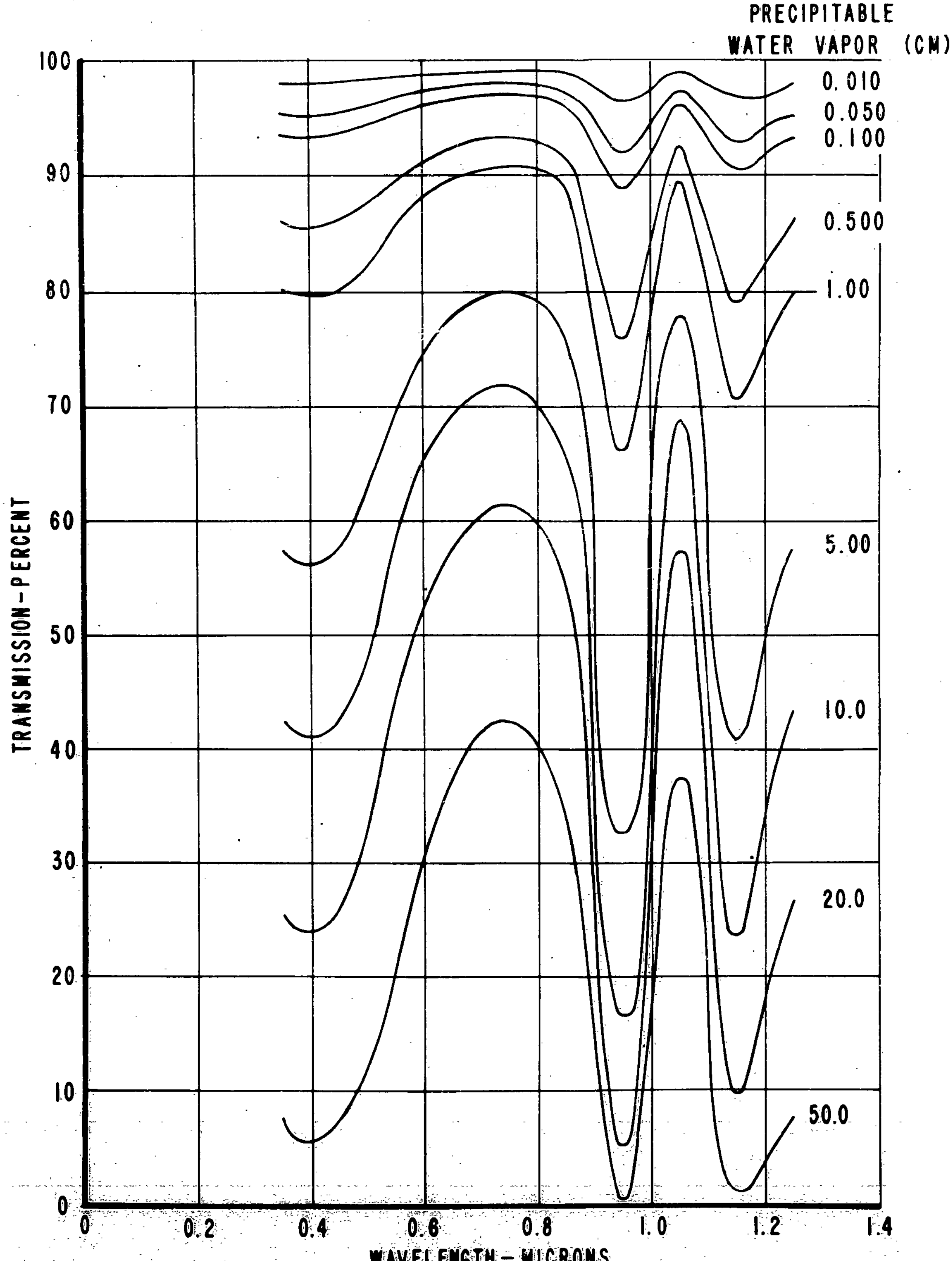


FIG. 4 - TRANSMISSION AS A FUNCTION OF HUMIDITY FOR A WAVELENGTH OF 0.35 MICRONS AND THE TEMPERATURE AT THE GIVEN HUMIDITY CORRESPONDING TO A RELATIVE HUMIDITY OF 70 PERCENT.

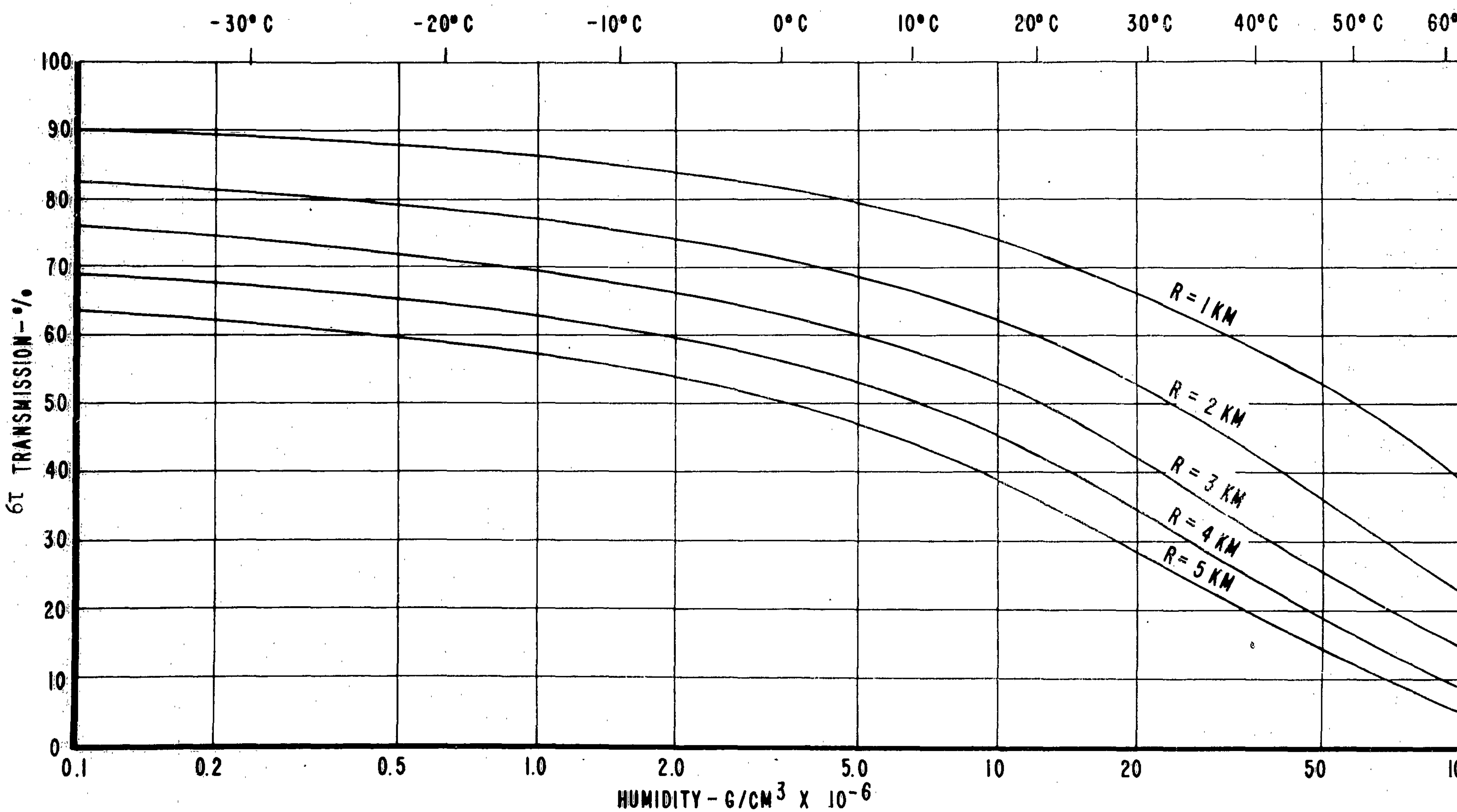


FIG. 5 – TRANSMISSION AS A FUNCTION OF HUMIDITY FOR A WAVELENGTH OF 0.40 MICRONS AND THE TEMPERATURE AT THE GIVEN HUMIDITY CORRESPONDING TO A RELATIVE HUMIDITY OF 70 PERCENT.

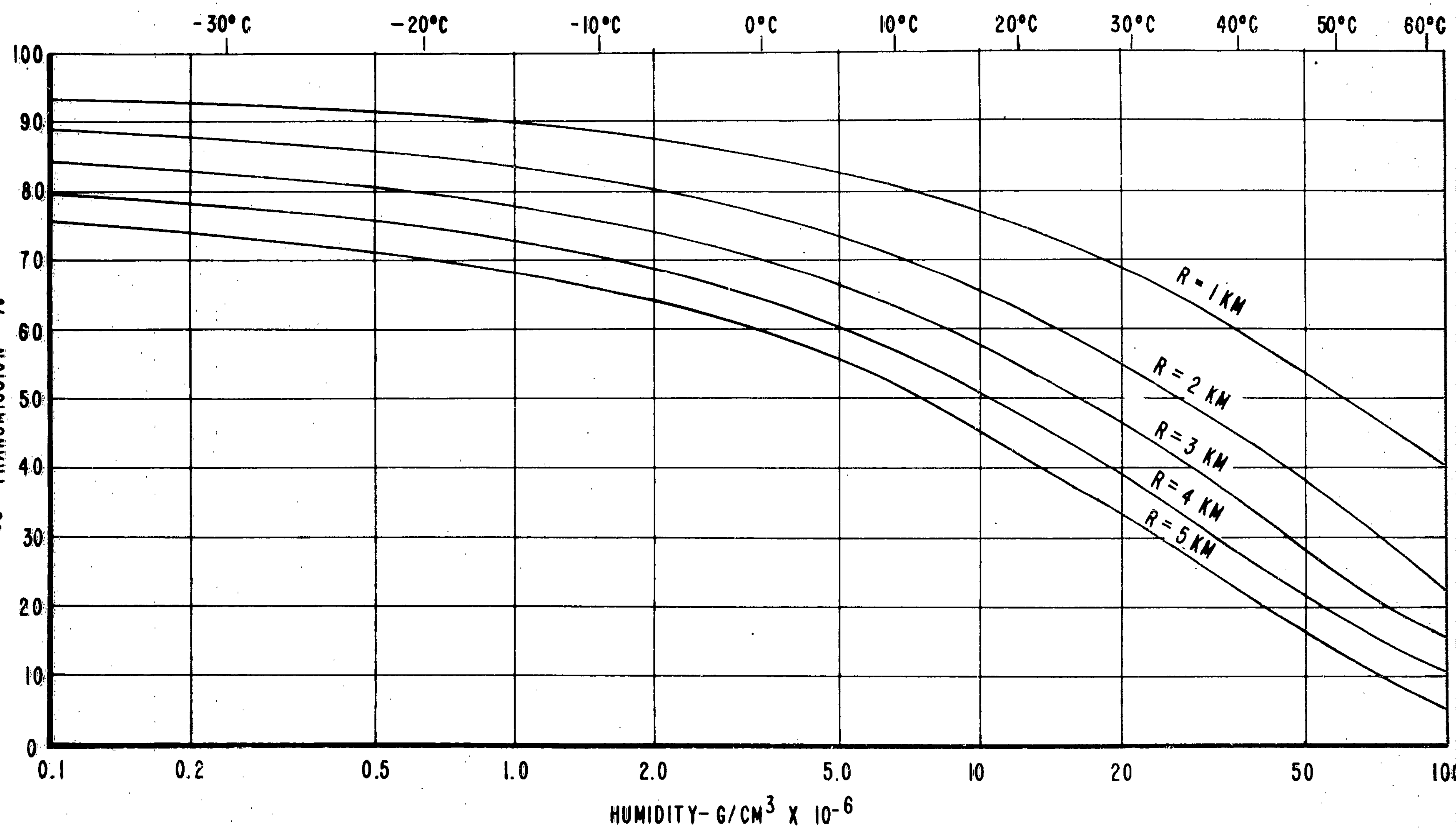


FIG. 6 – TRANSMISSION AS A FUCTION OF HUMIDITY FOR A WAVELENGTH OF 0.45 MICRONS AND THE TEMPERATURE AT THE GIVEN HUMIDITY CORRESPONDING TO A RELATIVE HUMIDITY OF 70 PER CENT.

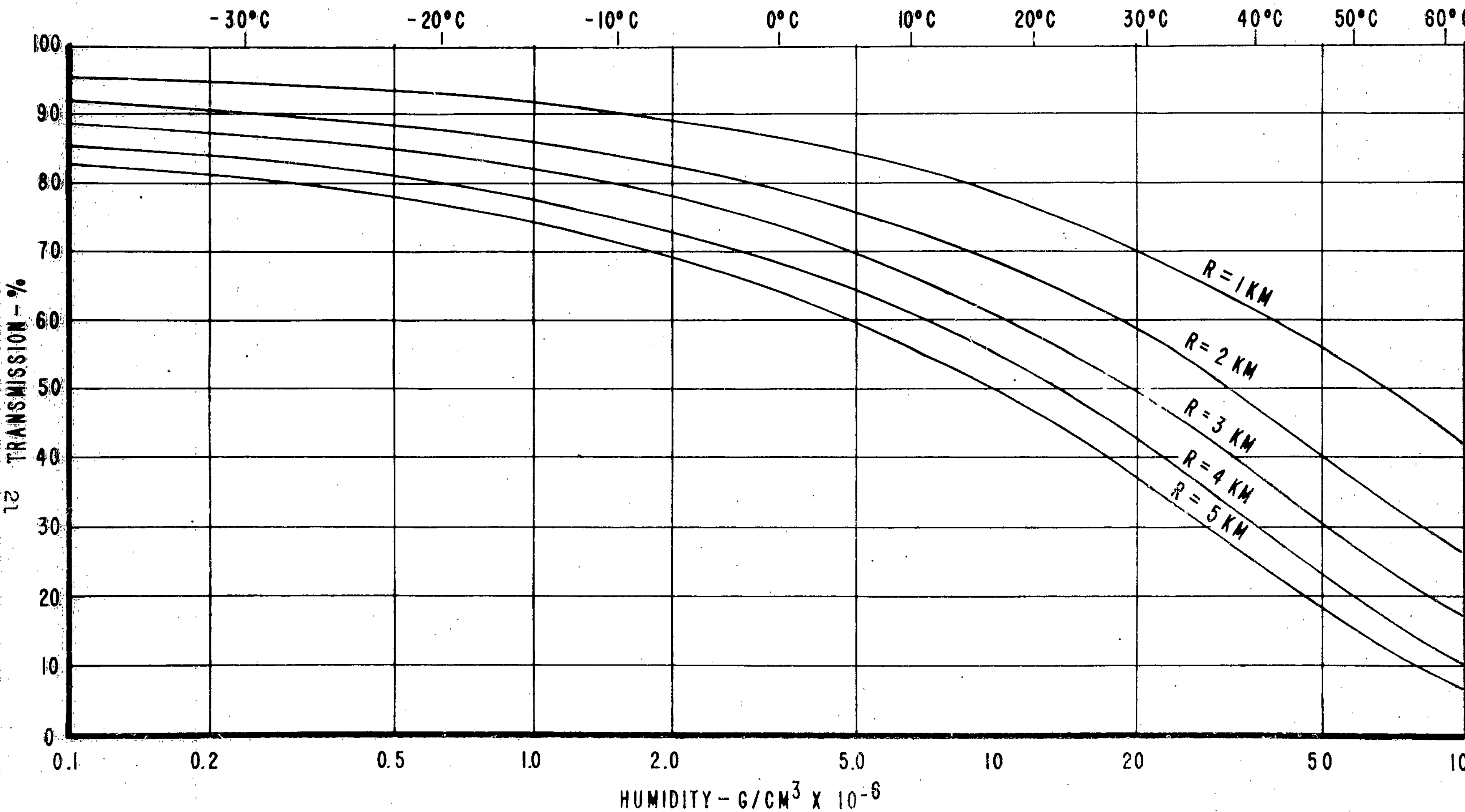


FIG. 7 — TRANSMISSION AS A FUNCTION OF HUMIDITY FOR A WAVELENGTH OF 0.50 MICRONS AND THE TEMPERATURE AT THE GIVEN HUMIDITY CORRESPONDING TO A RELATIVE HUMIDITY OF 70 PERCENT.

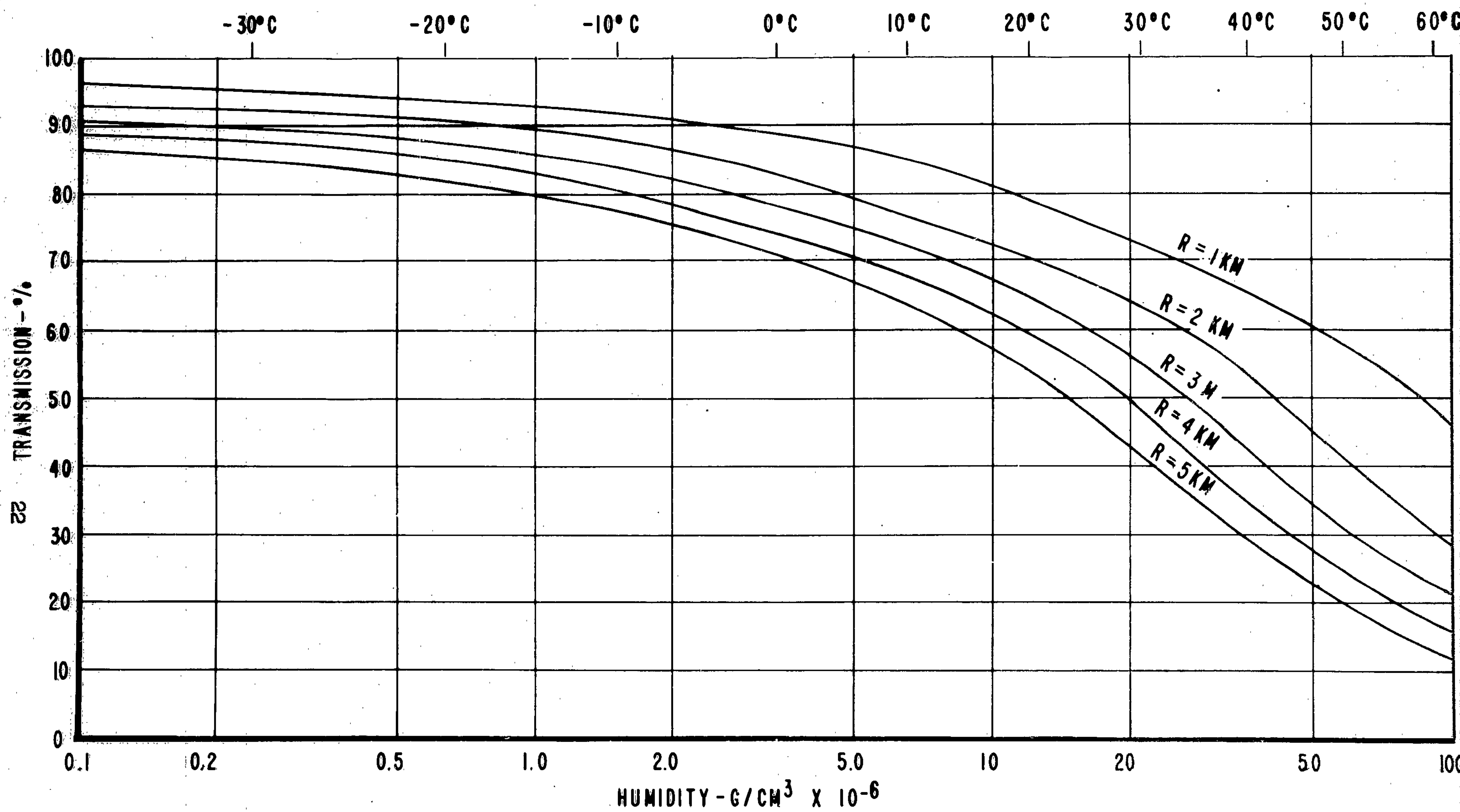


FIG. 8 - TRANSMISSION AS A FUNCTION OF HUMIDITY FOR A WAVELENGTH OF 0.55 MICRONS AND THE TEMPERATURE AT THE GIVEN HUMIDITY CORRESPONDING TO A RELATIVE HUMIDITY OF 70 PERCENT.

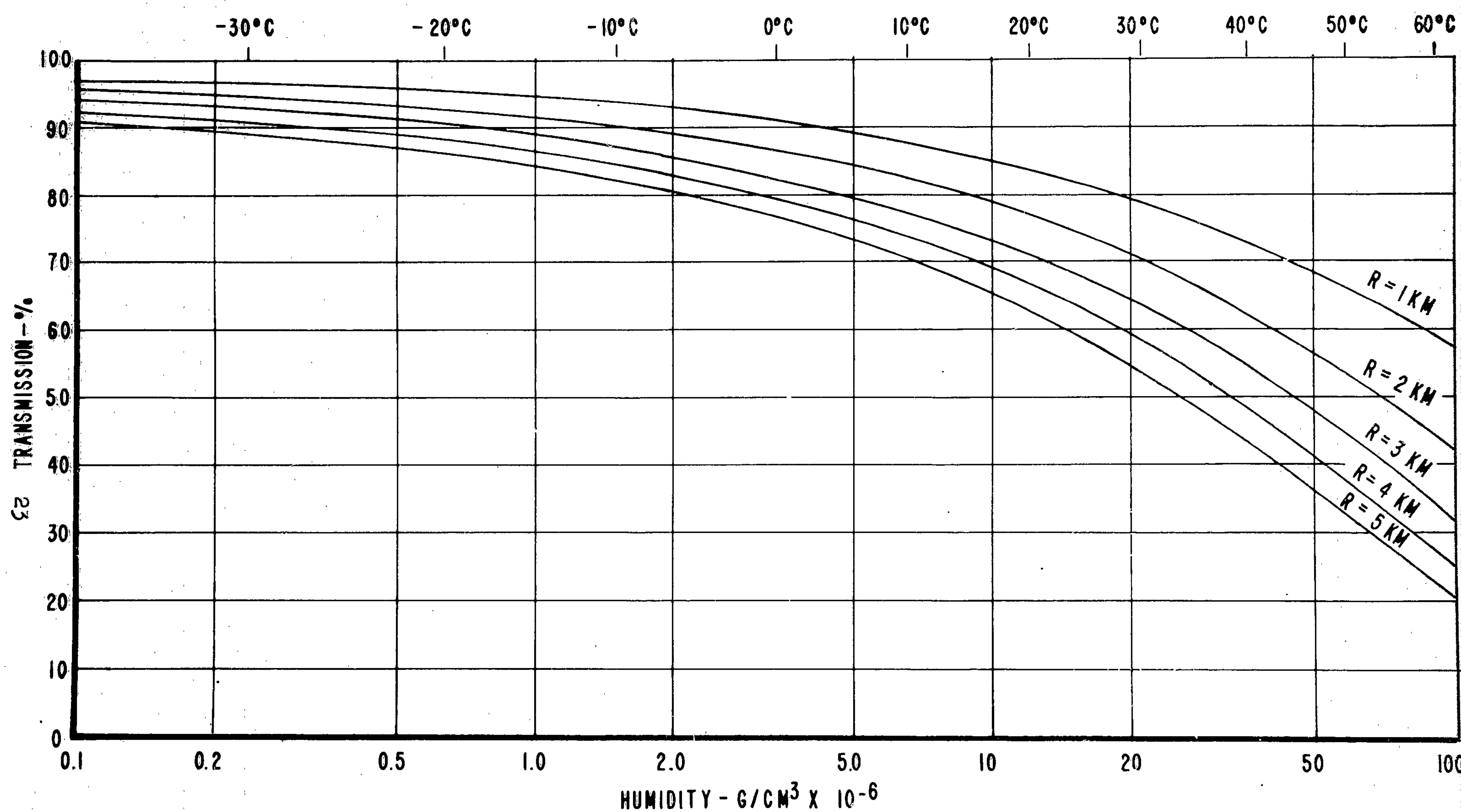


FIG. 9 - TRANSMISSION AS A FUNCTION OF HUMIDITY FOR A WAVELENGTH OF 0.60 MICRONS AND THE TEMPERATURE AT THE GIVEN HUMIDITY CORRESPONDING TO RELATIVE HUMIDITY OF 70 PERCENT.

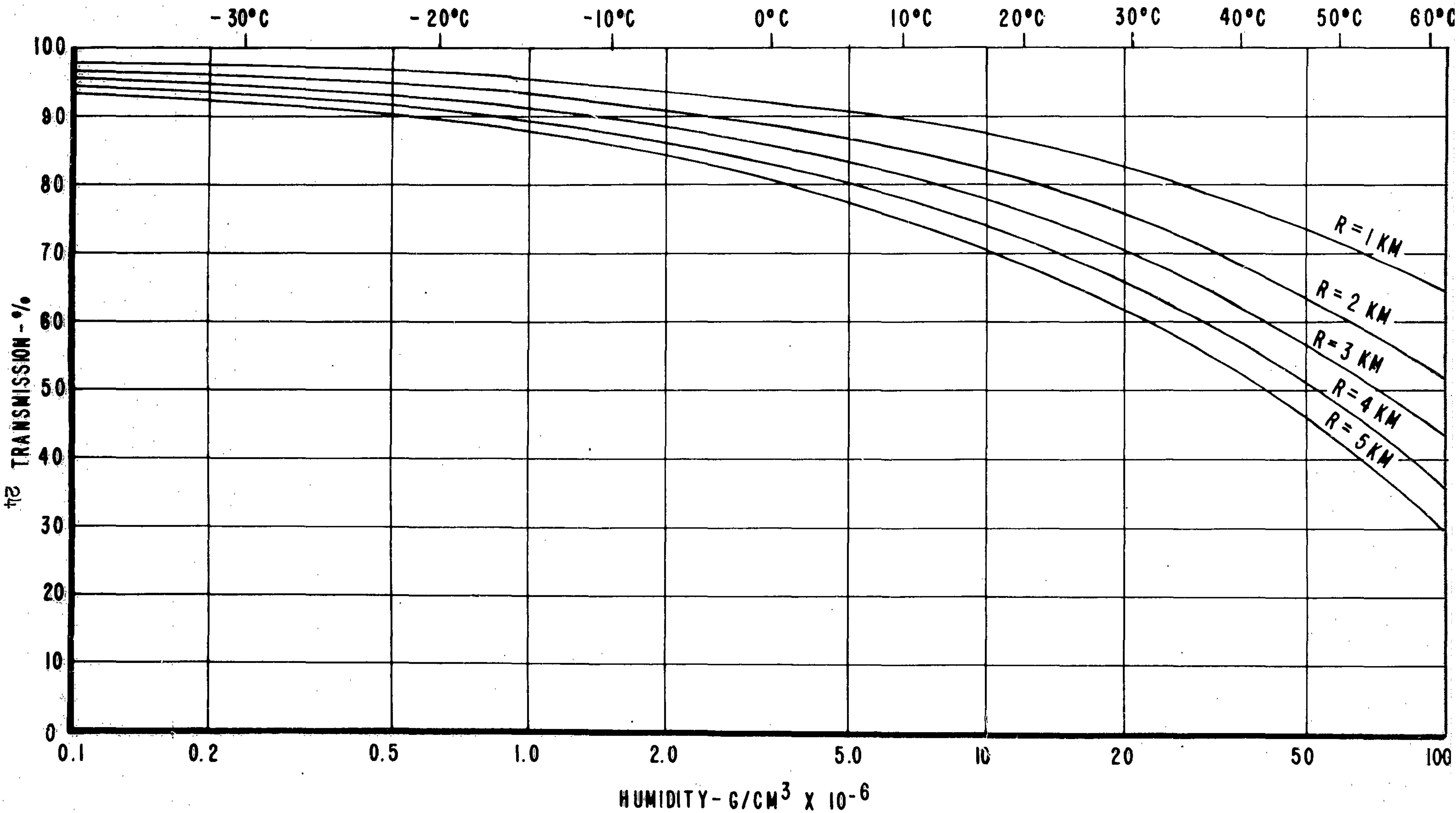


FIG. 10 – TRANSMISSION AS A FUNCTION OF HUMIDITY FOR A WAVELENGTH OF 0.65 MICRONS AND THE TEMPERATURE AT THE GIVEN HUMIDITY CORRESPONDING TO A RELATIVE HUMIDITY OF 70 PERCENT.

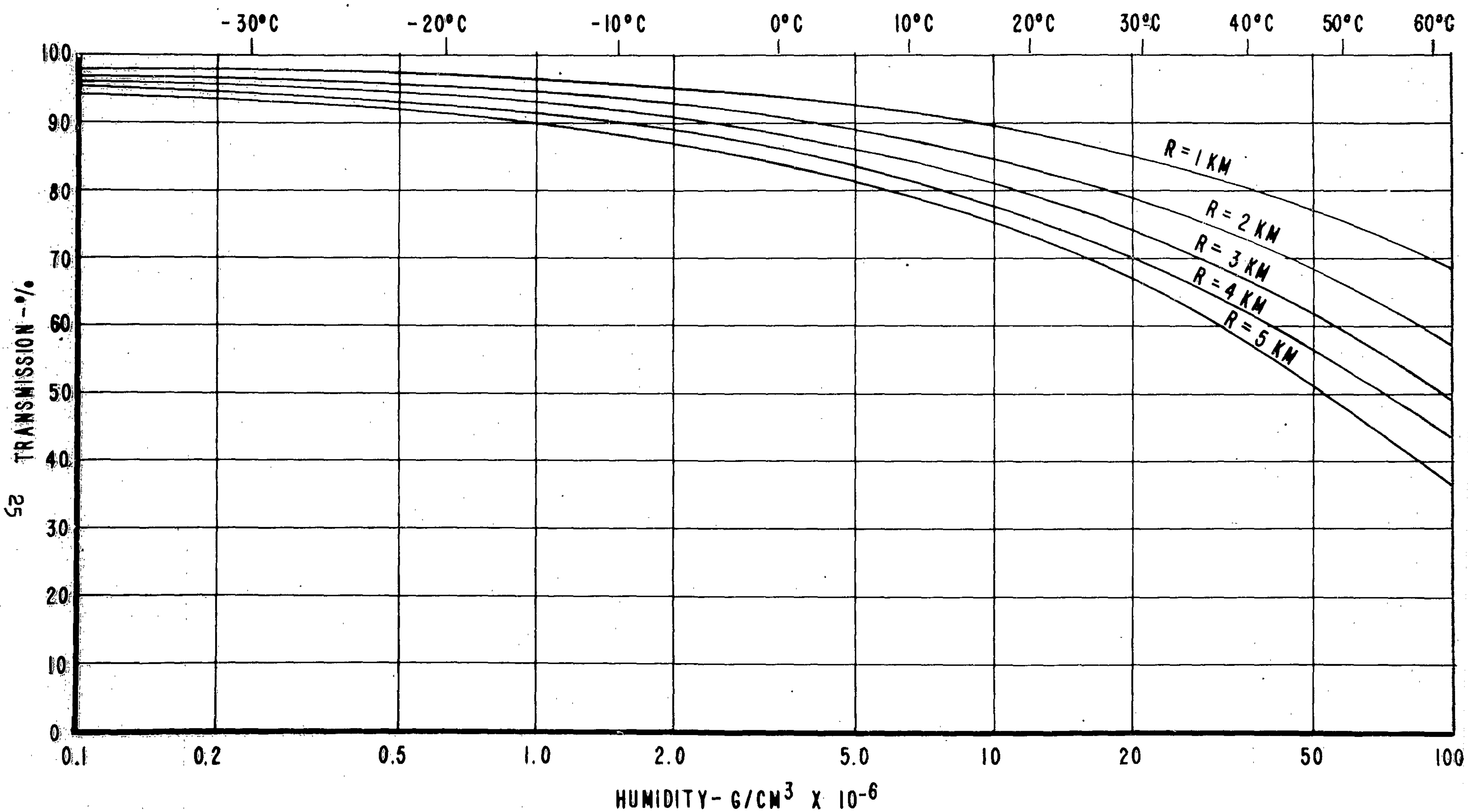


FIG. 11 – TRANSMISSION AS A FUNCTION OF HUMIDITY FOR A WAVELENGTH OF 0.70 MICRONS AND THE TEMPERATURE AT THE GIVEN HUMIDITY CORRESPONDING TO A RELATIVE HUMIDITY OF 70 PERCENT.

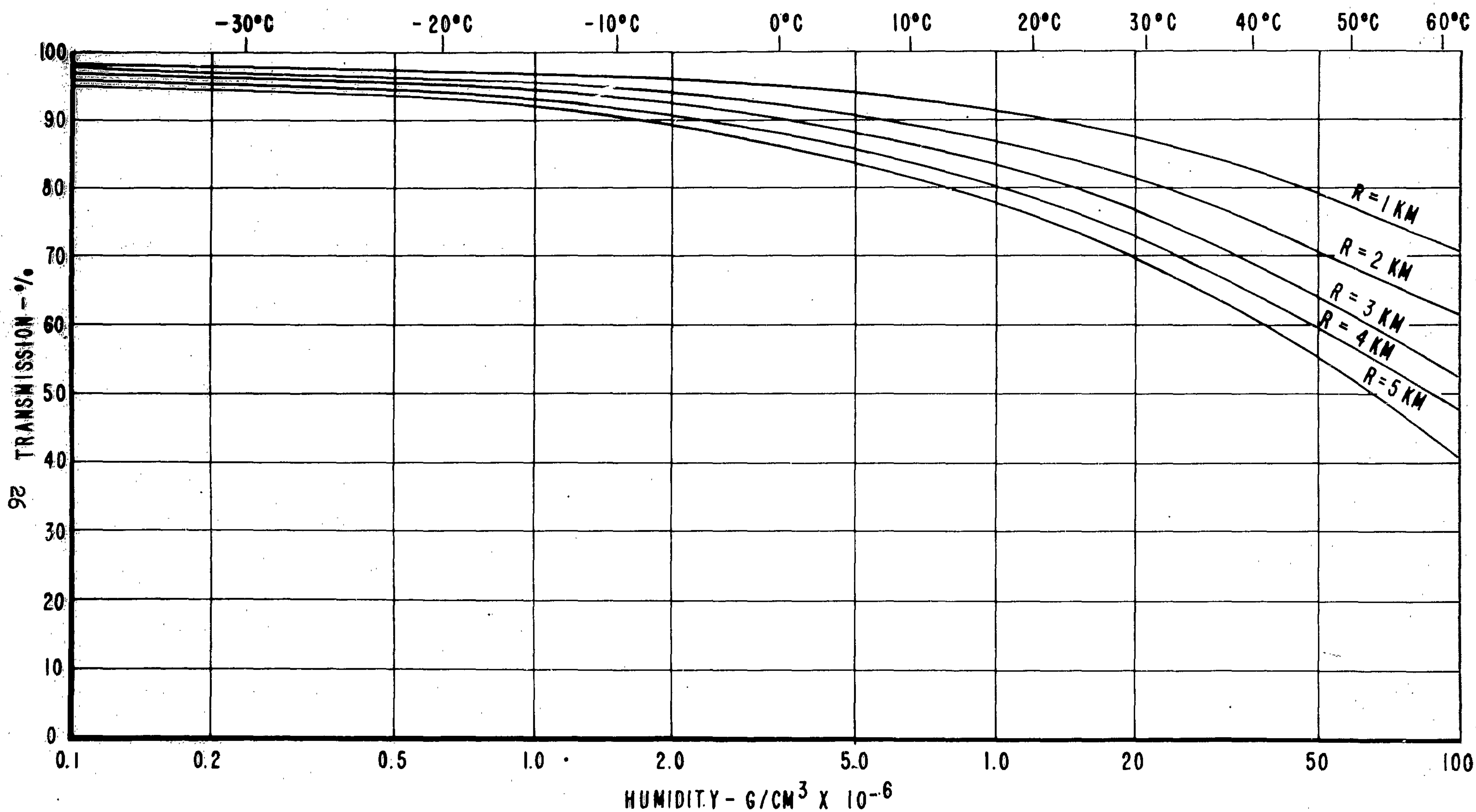


FIG. 12 - TRANSMISSION AS A FUNCTION OF HUMIDITY FOR A WAVELENGTH OF 0.75 MICRONS AND THE TEMPERATURE AT THE GIVEN HUMIDITY CORRESPONDING TO A RELATIVE HUMIDITY OF 70 PERCENT.

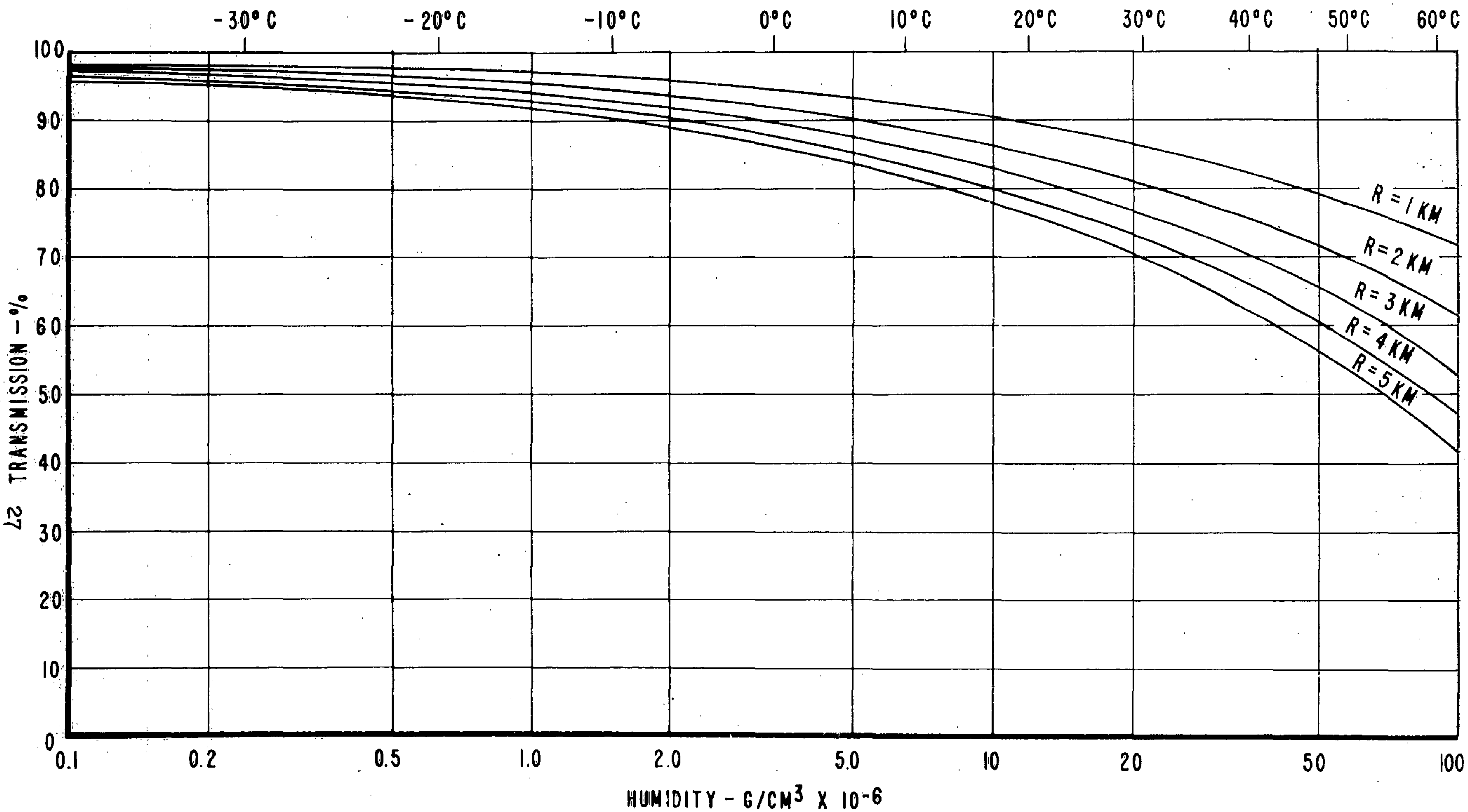


FIG. 13 - TRANSMISSION AS A FUNCTION OF HUMIDITY FOR A WAVELENGTH OF 0.80 MICRONS AND THE TEMPERATURE AT THE GIVEN HUMIDITY CORRESPONDING TO A RELATIVE HUMIDITY OF 70 PERCENT.

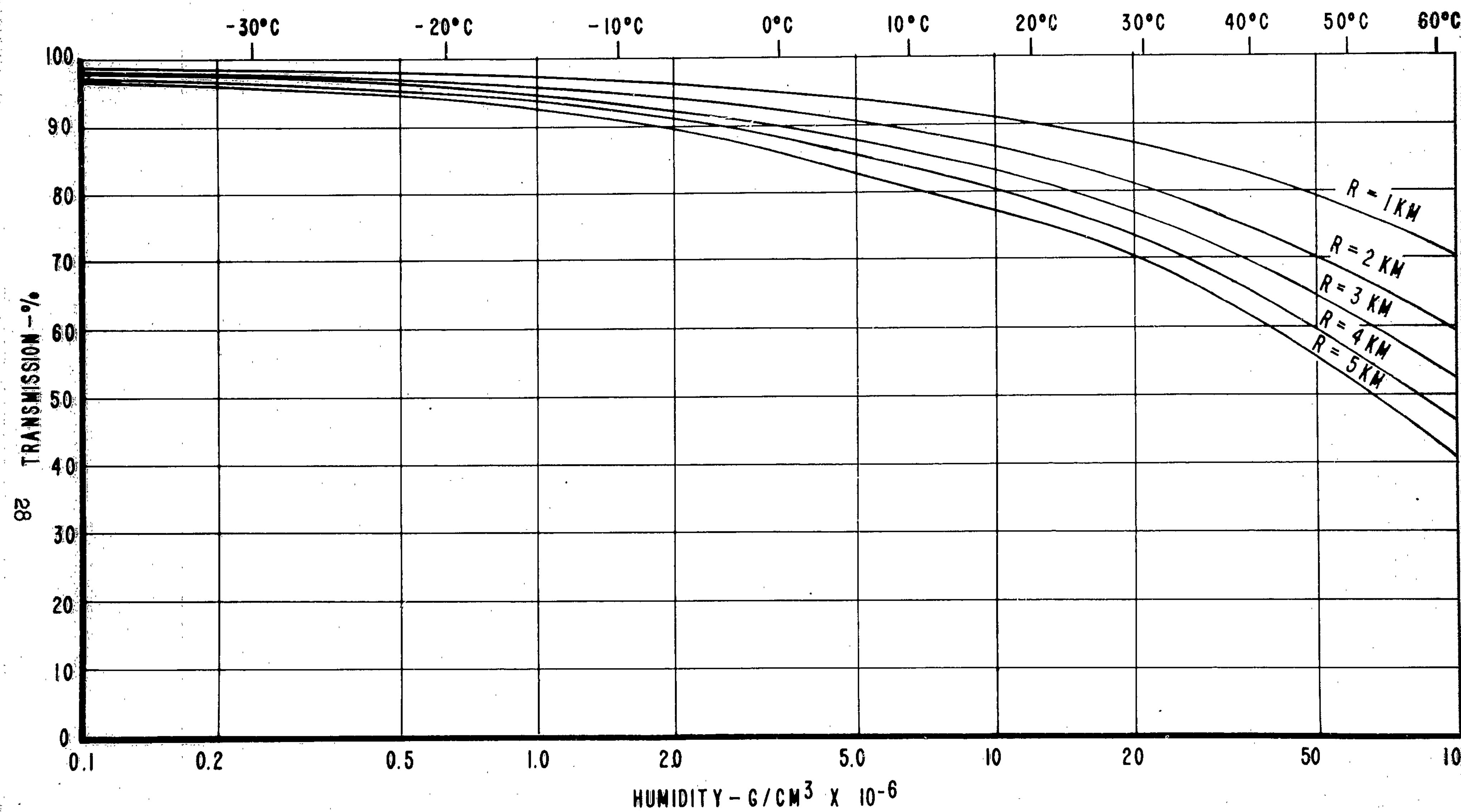


FIG. 14 - TRANSMISSION AS A FUNCTION OF HUMIDITY FOR A WAVELENGTH OF 0.85 MICRONS AND THE TEMPERATURE AT THE GIVEN HUMIDITY CORRESPONDING TO A RELATIVE HUMIDITY OF 70 PERCENT.

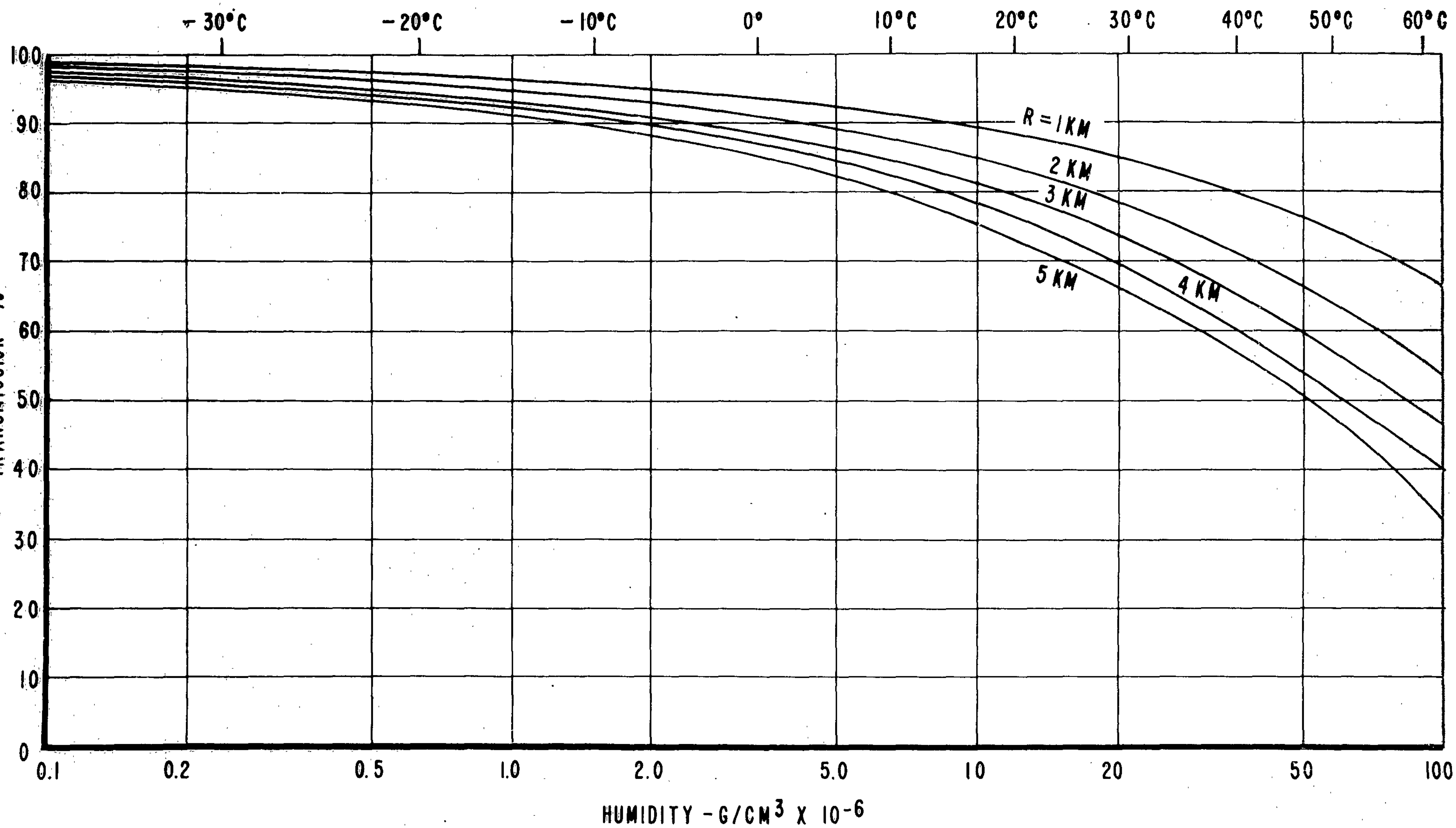


FIG. 15 - TRANSMISSION AS A FUNCTION OF HUMIDITY FOR A WAVELENGTH OF 0.90 MICRONS AND THE TEMPERATURE AT THE GIVEN HUMIDITY, CORRESPONDING TO A RELATIVE HUMIDITY OF 70 PERCENT.

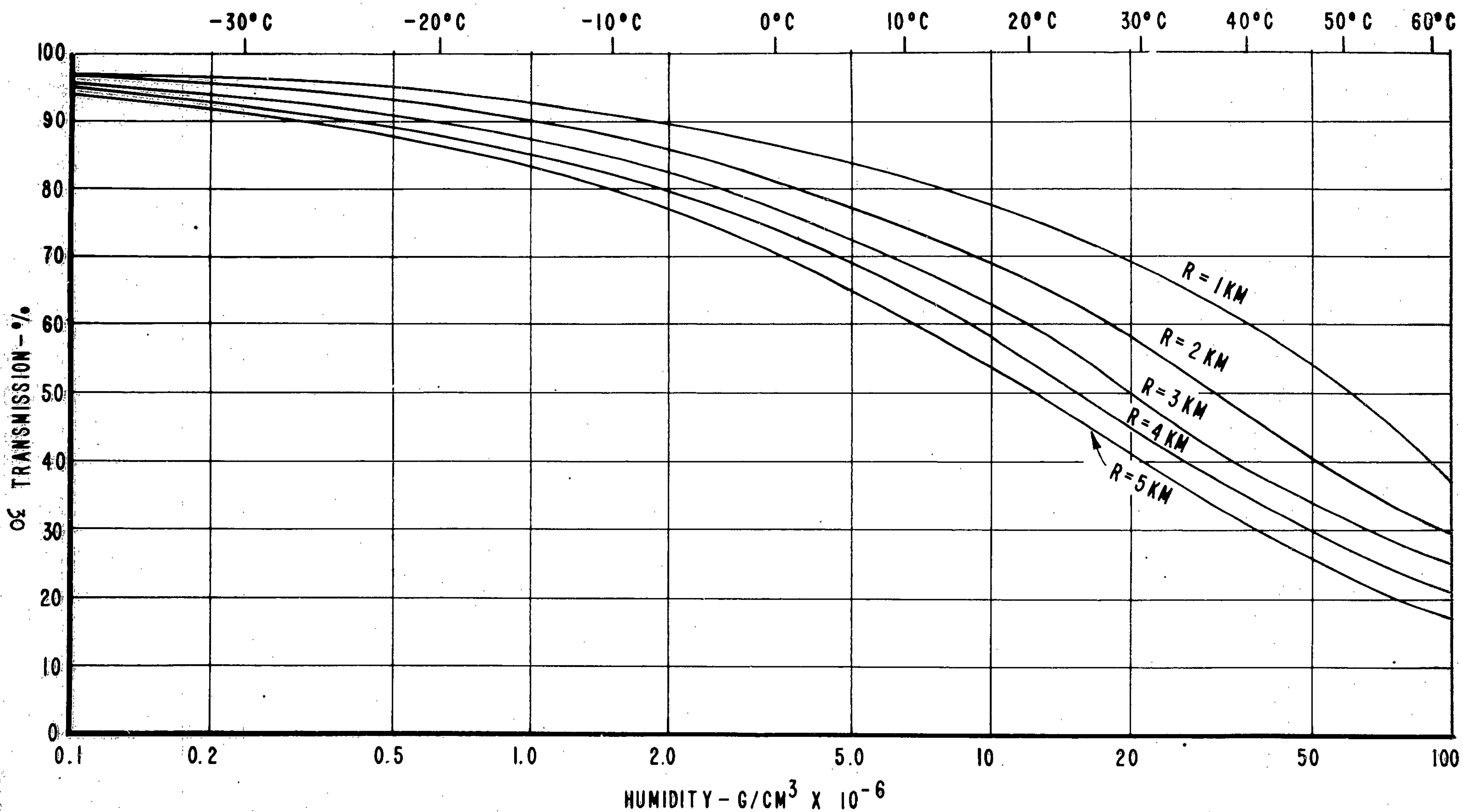
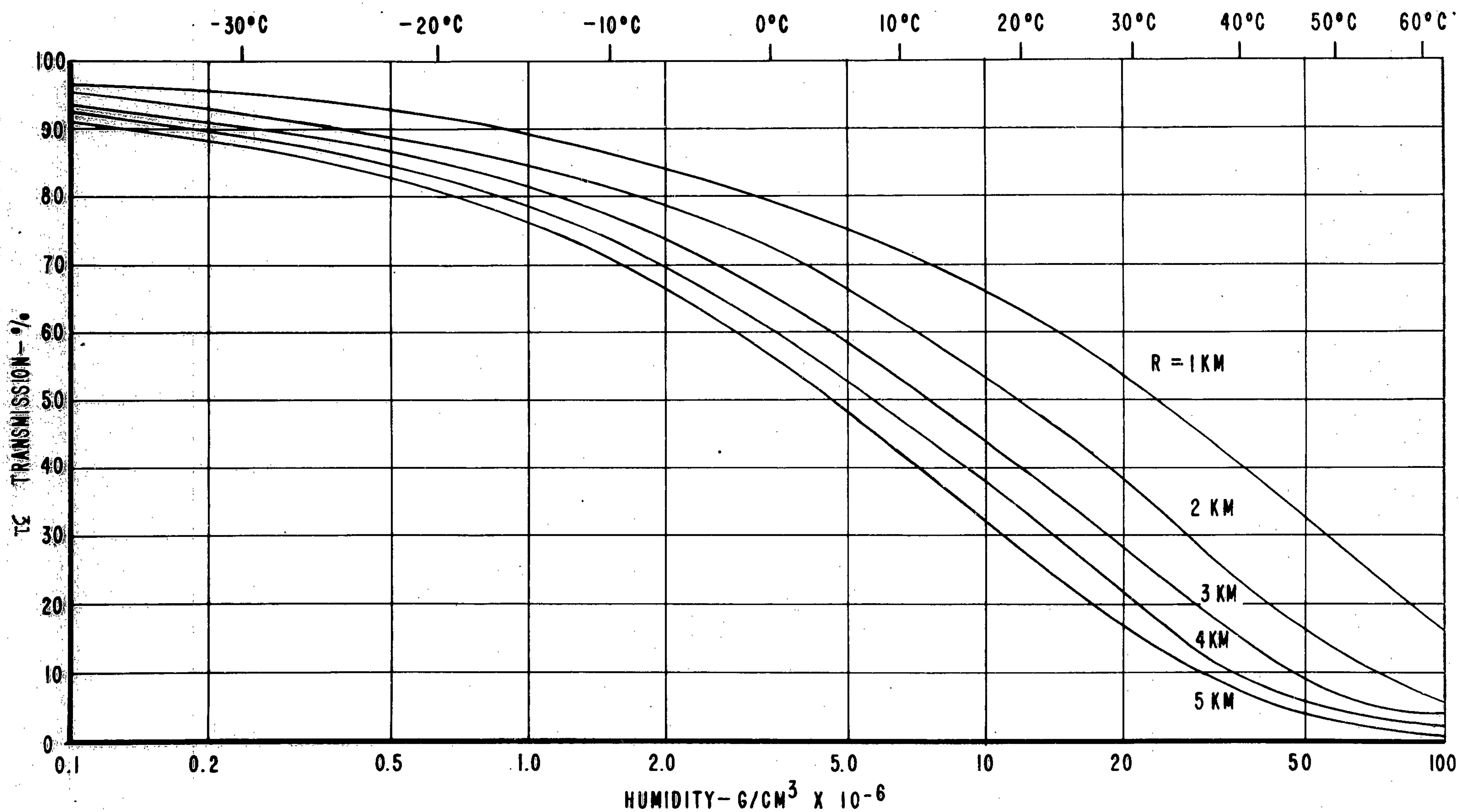


FIG. 16—TRANSMISSION AS A FUNCTION OF HUMIDITY FOR A WAVELENGTH OF 0.95 MICRONS AND THE TEMPERATURE AT THE GIVEN HUMIDITY CORRESPONDING TO A RELATIVE HUMIDITY OF 70 PERCENT.



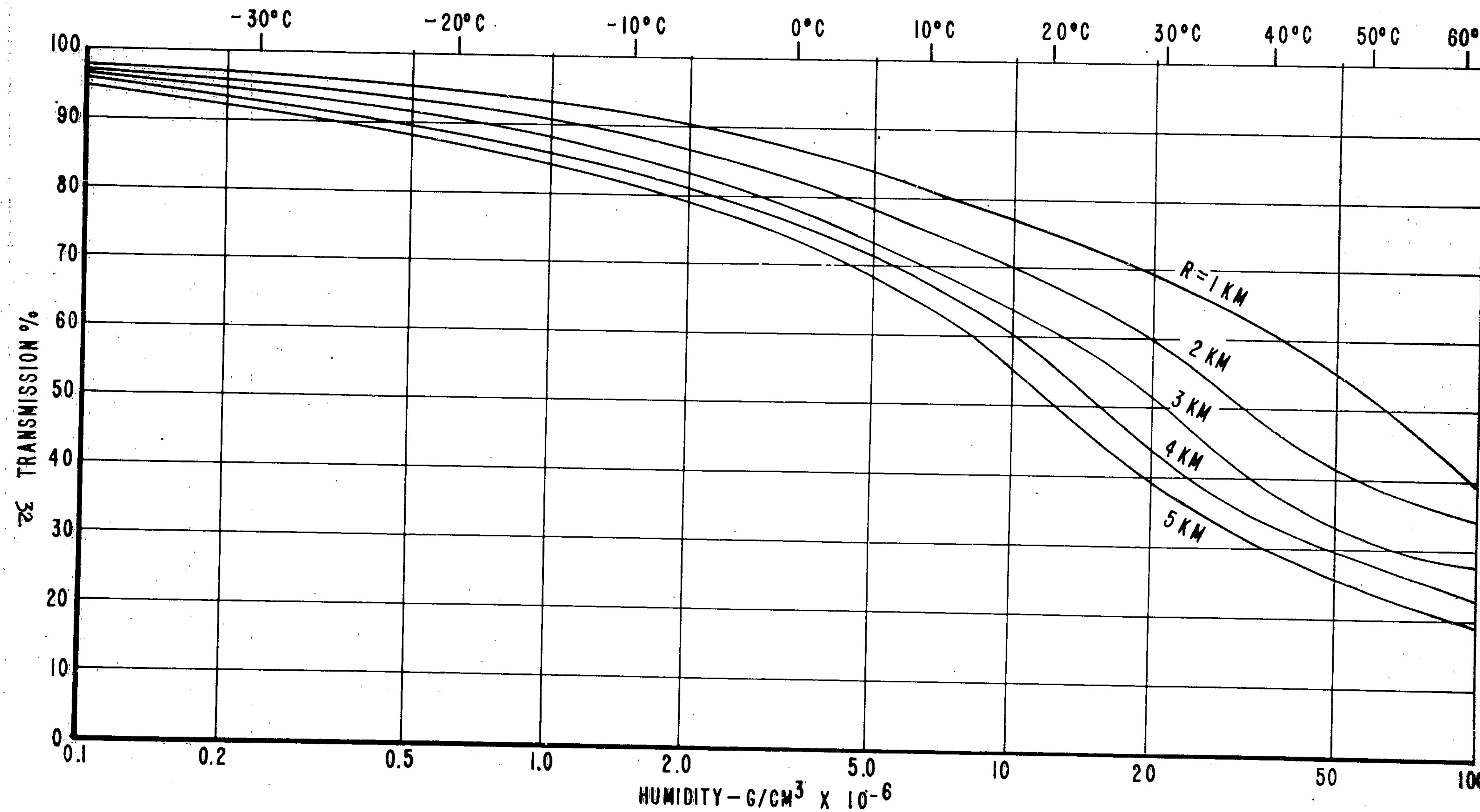


FIG. 17—TRANSMISSION AS A FUNCTION OF HUMIDITY FOR A WAVELENGTH OF 1.00 MICRONS AND THE TEMPERATURE AT THE GIVEN HUMIDITY CORRESPONDING TO A RELATIVE HUMIDITY OF 70 PER CENT.

FIG. 18- TRANSMISSION AS A FUNCTION OF HUMIDITY FOR A WAVELENGTH OF 1.05 MICRONS AND THE TEMPERATURE AT THE GIVEN HUMIDITY CORRESPONDING TO A RELATIVE HUMIDITY OF 70 PERCENT.

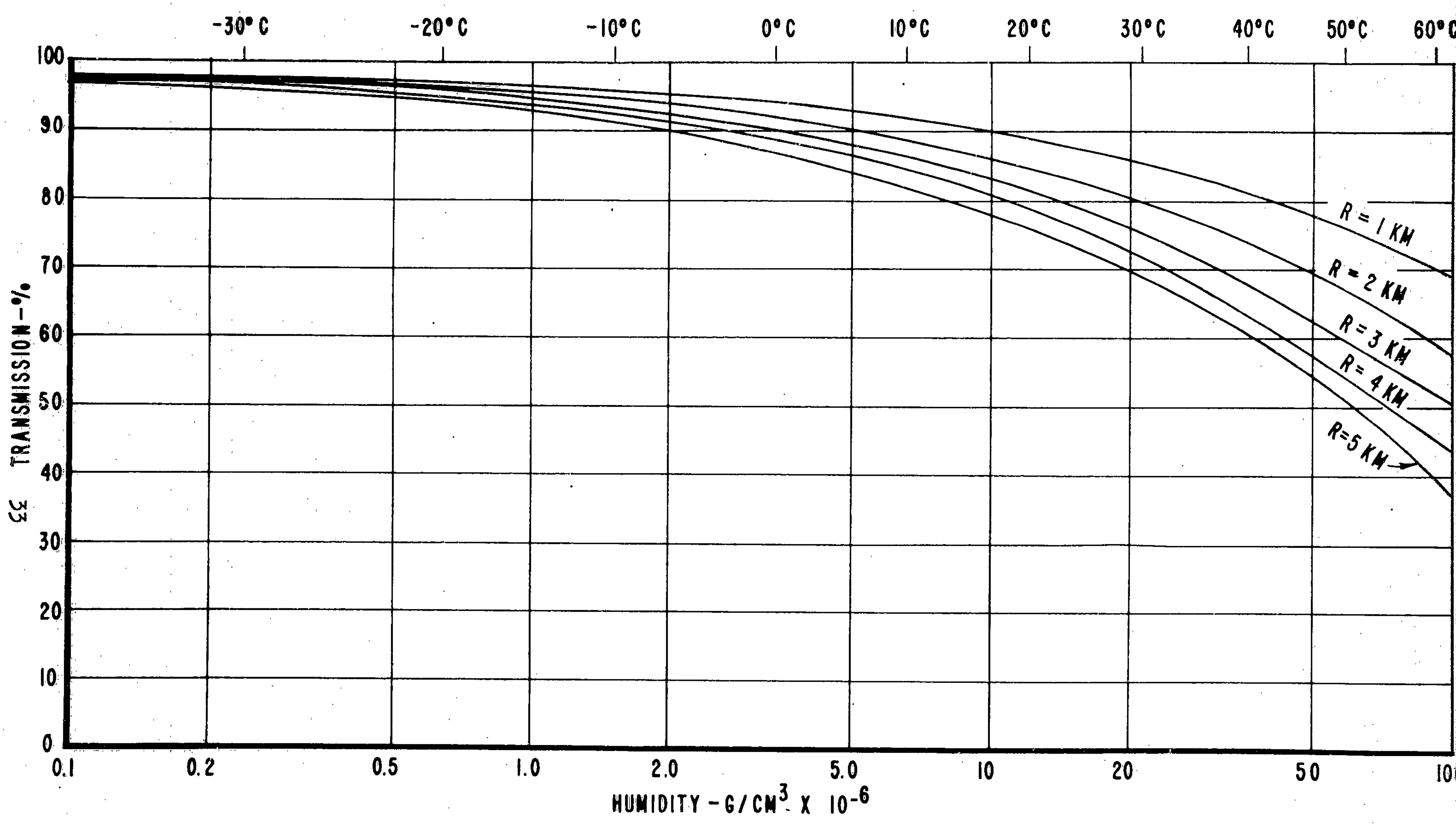


FIG. 19 - TRANSMISSION AS A FUNCTION OF HUMIDITY FOR A WAVELENGTH OF 1.10 MICRONS AND THE TEMPERATURE AT THE GIVEN HUMIDITY CORRESPONDING TO A RELATIVE HUMIDITY OF 70 PERCENT.

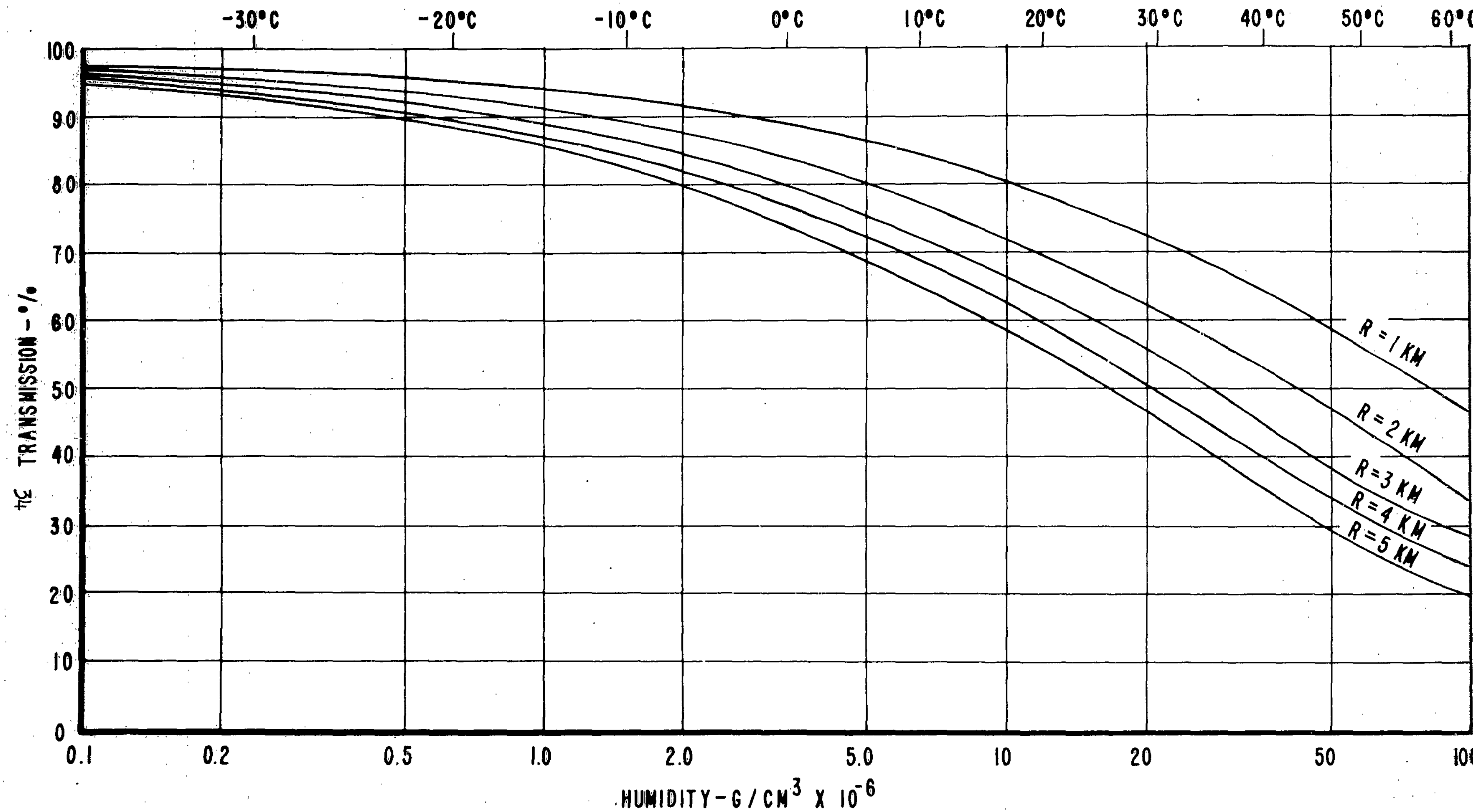


FIG. 20 - HUMIDITY AS A FUNCTION OF TEMPERATURE FOR RELATIVE HUMIDITIES BETWEEN 5 AND 100 PERCENT.

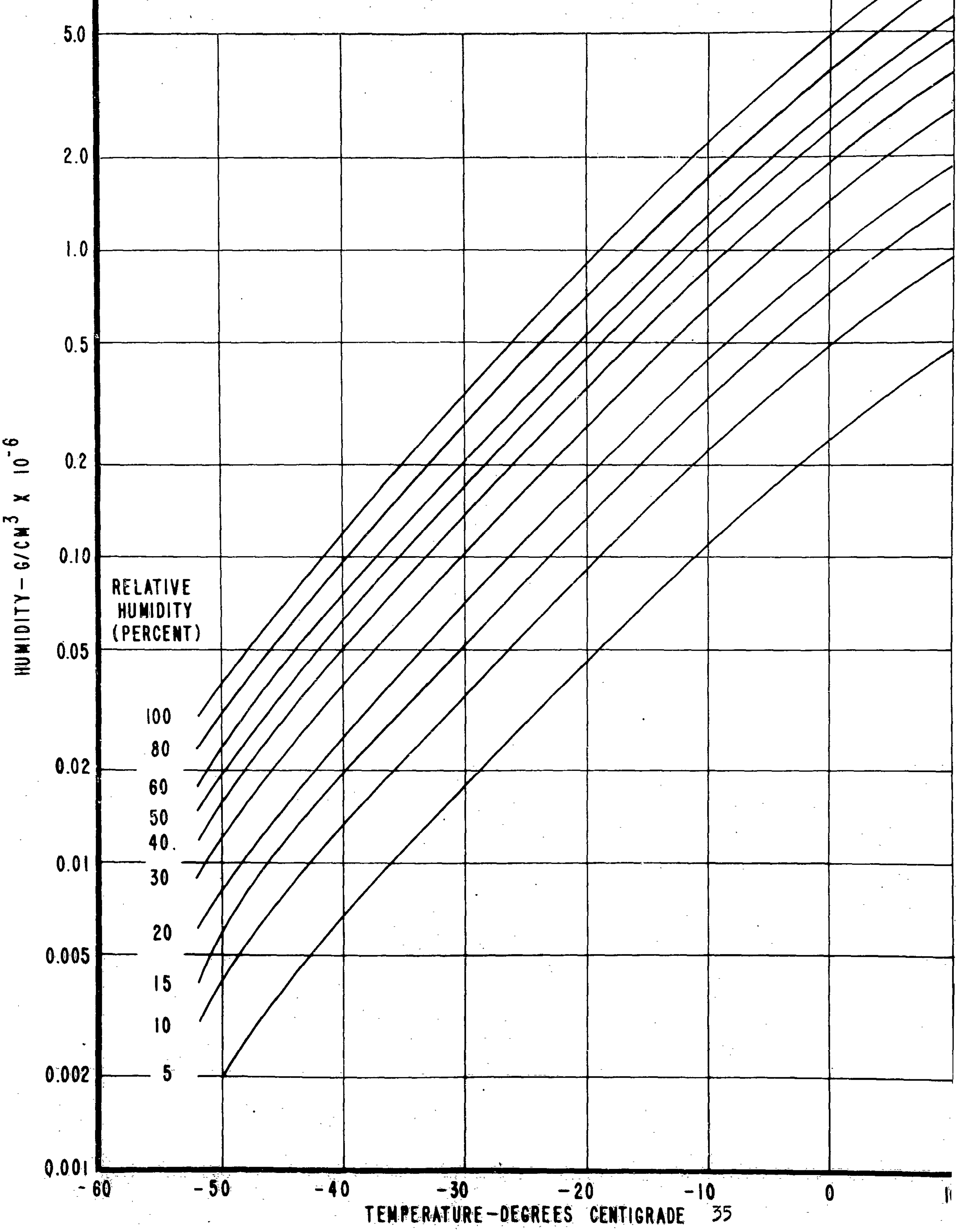


FIG. 21–HUMIDITY AS A FUNCTION OF TEMPERATURE FOR RELATIVE HUMIDITIES BETWEEN 5 AND 100 PERCENT.

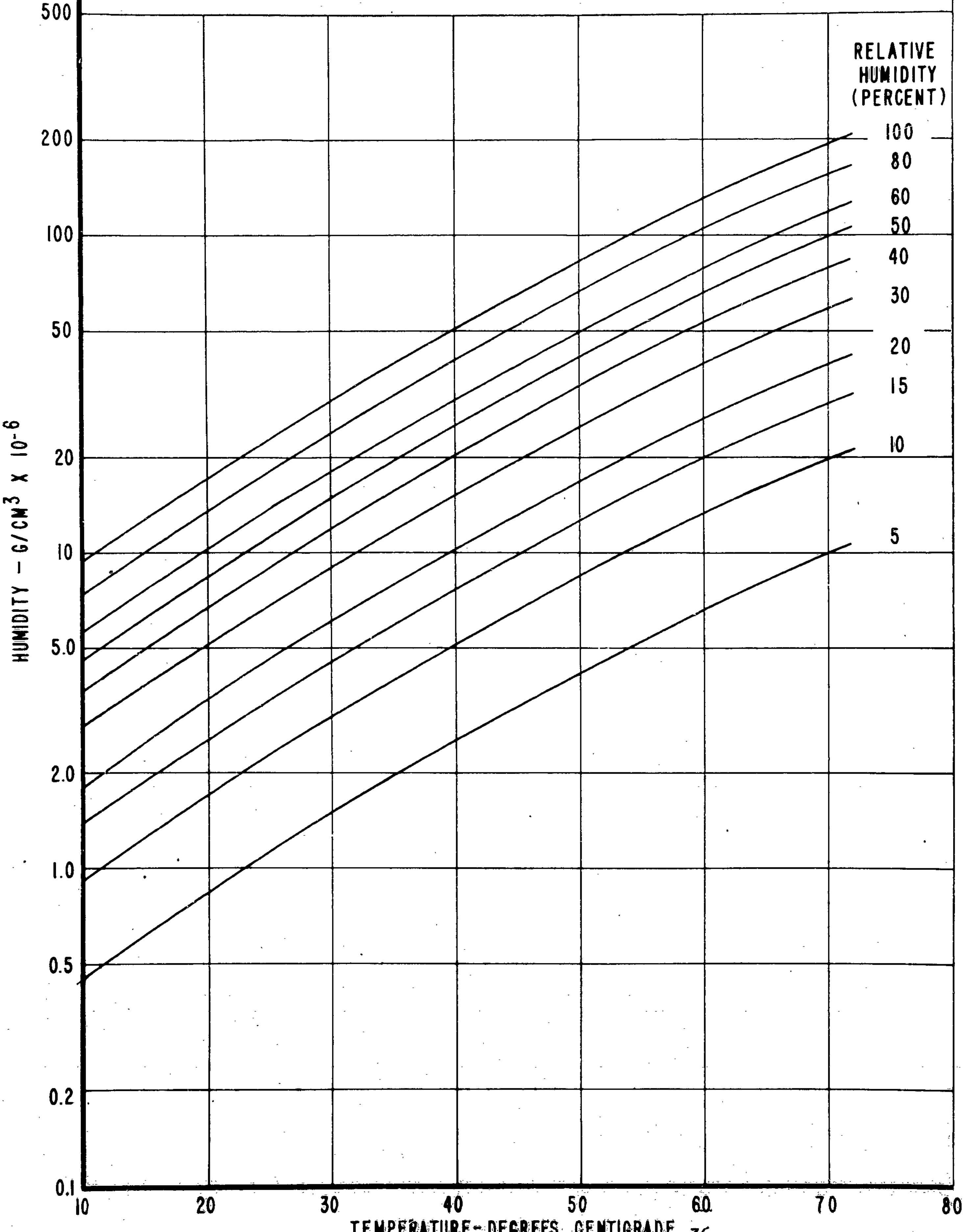


FIG. 22– THE SCATTERING AREA COEFFICIENT, K_r, AS A FUNCTION OF $2\pi r/\lambda$ AFTER HOUGHTON AND CHALKER.

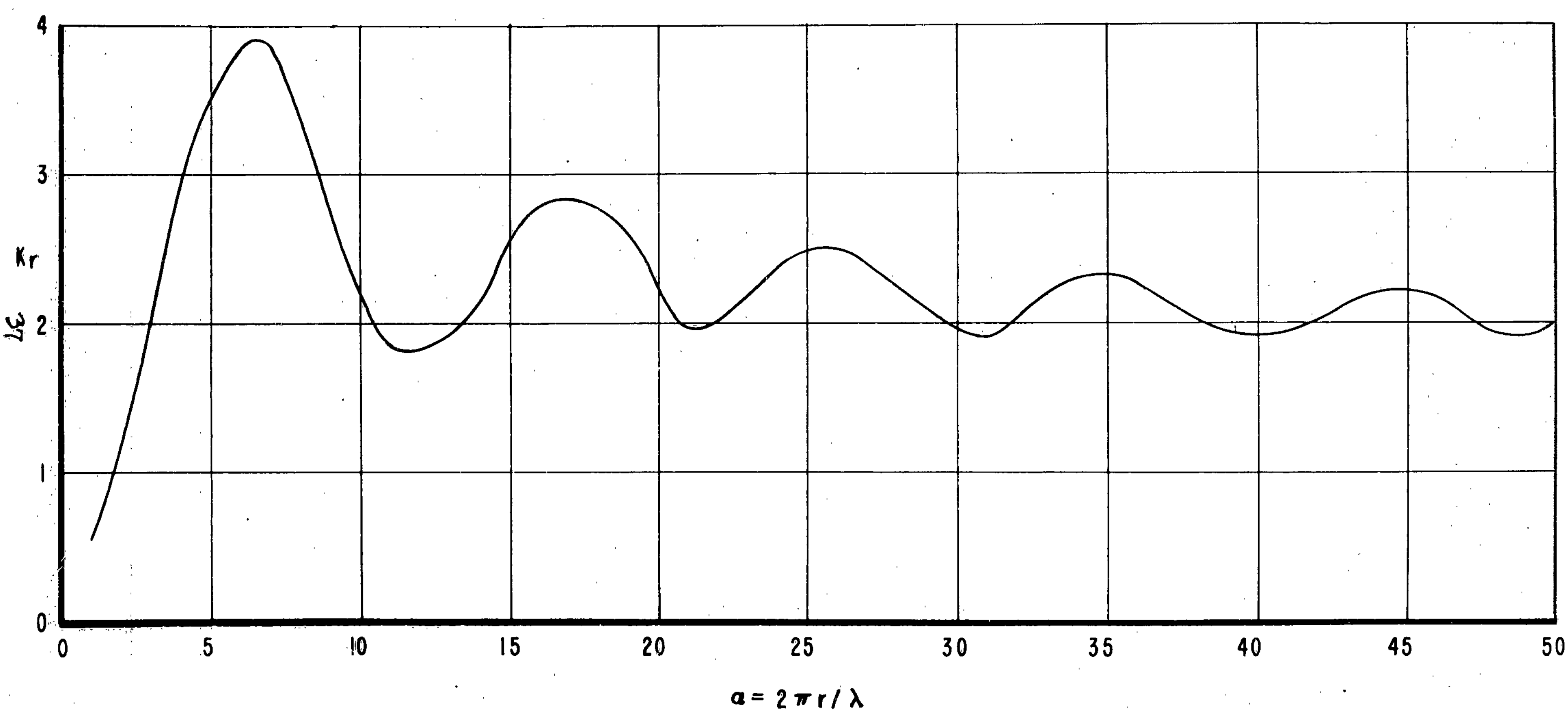


FIG. 23 - TRANSMISSION AS A FUNCTION OF RANGE FOR A VARIETY OF FOGS

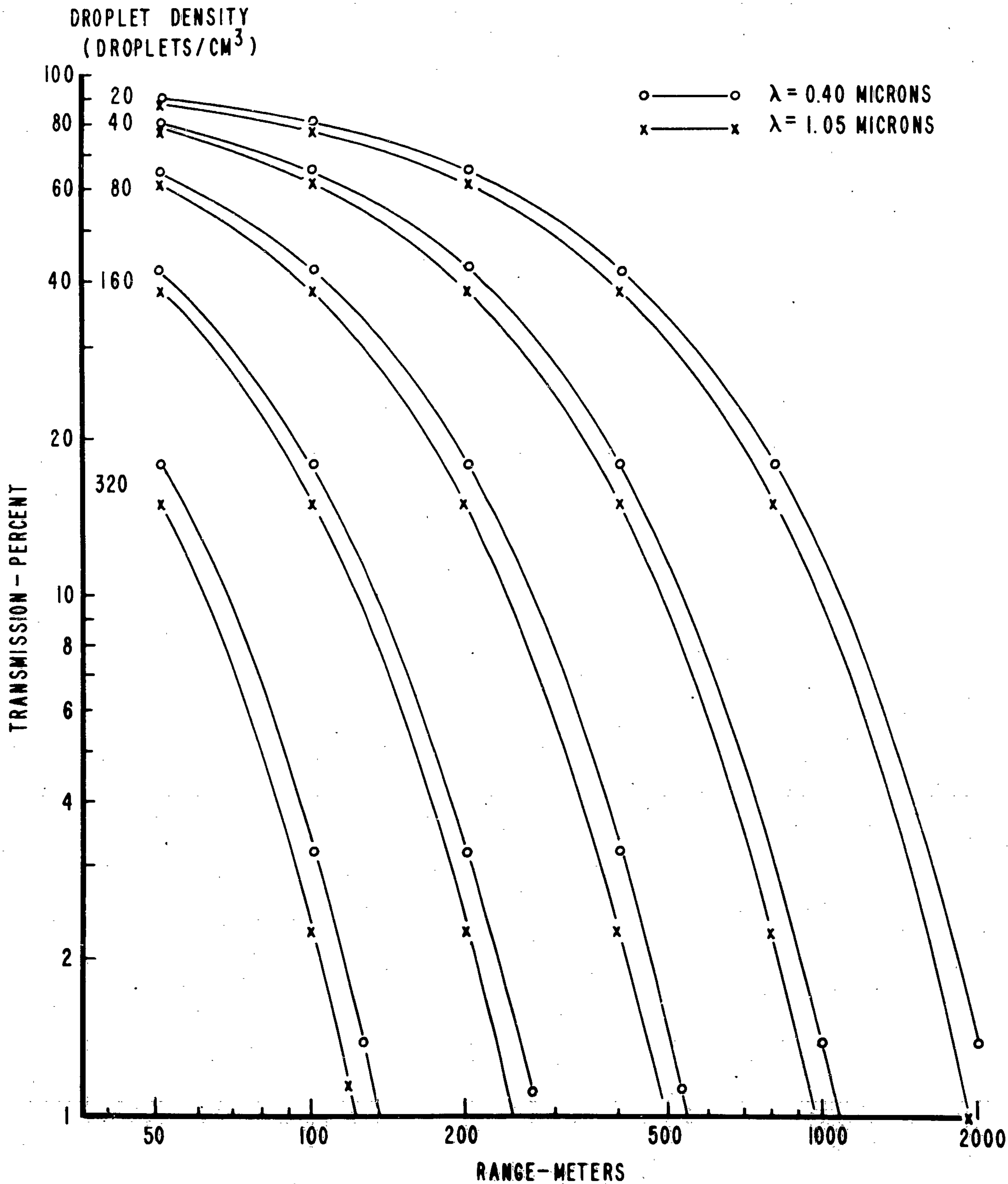


FIG. 24 – TRANSMISSION AS A FUNCTION OF RANGE FOR A VARIETY OF FOGS.

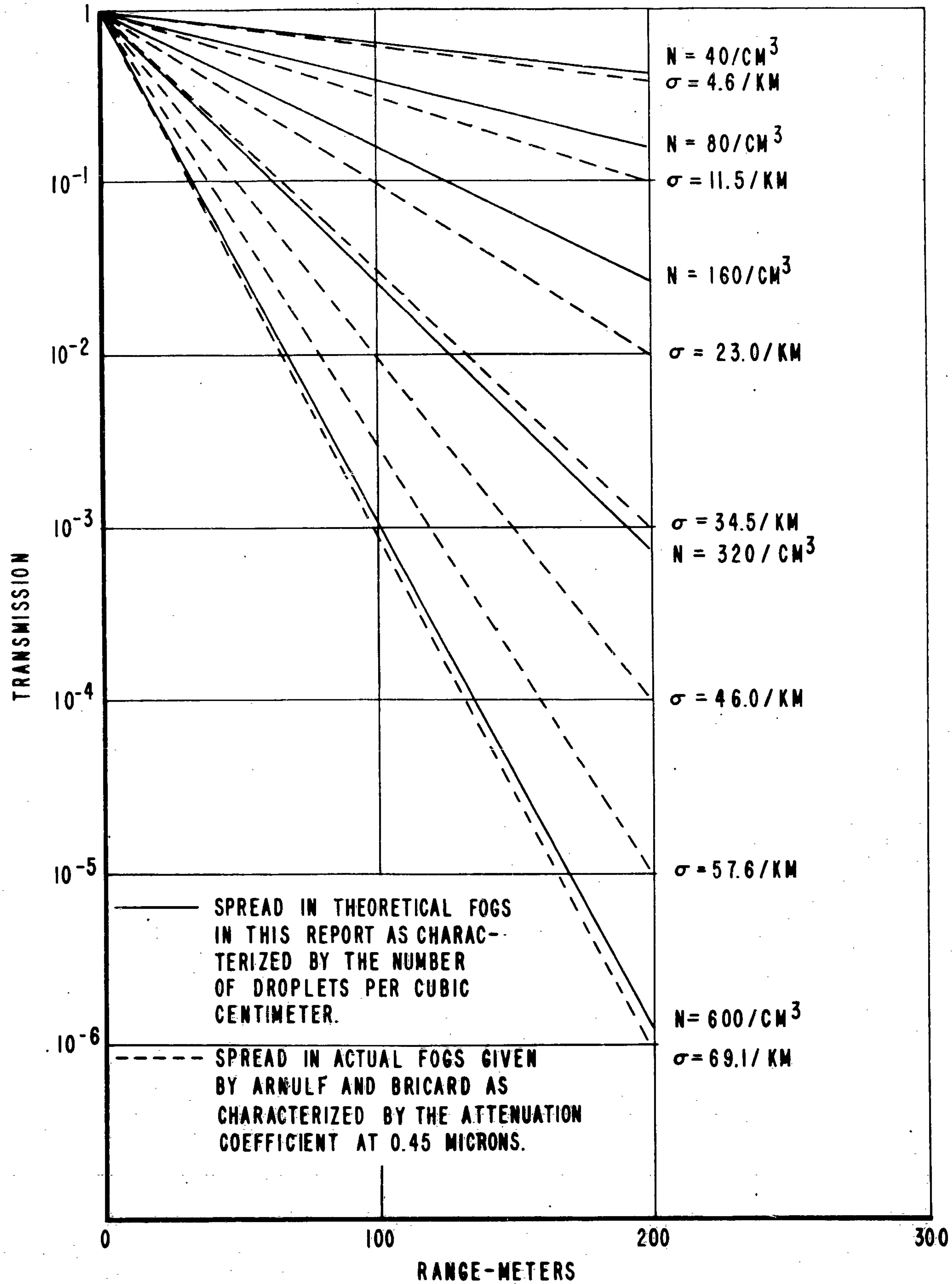


FIG. 25 TRANSMISSION ACROSS THE GIVEN PATH LENGTH BY AN ATMOSPHERE CHARACTERIZED BY THE GIVEN VISUAL RANGE

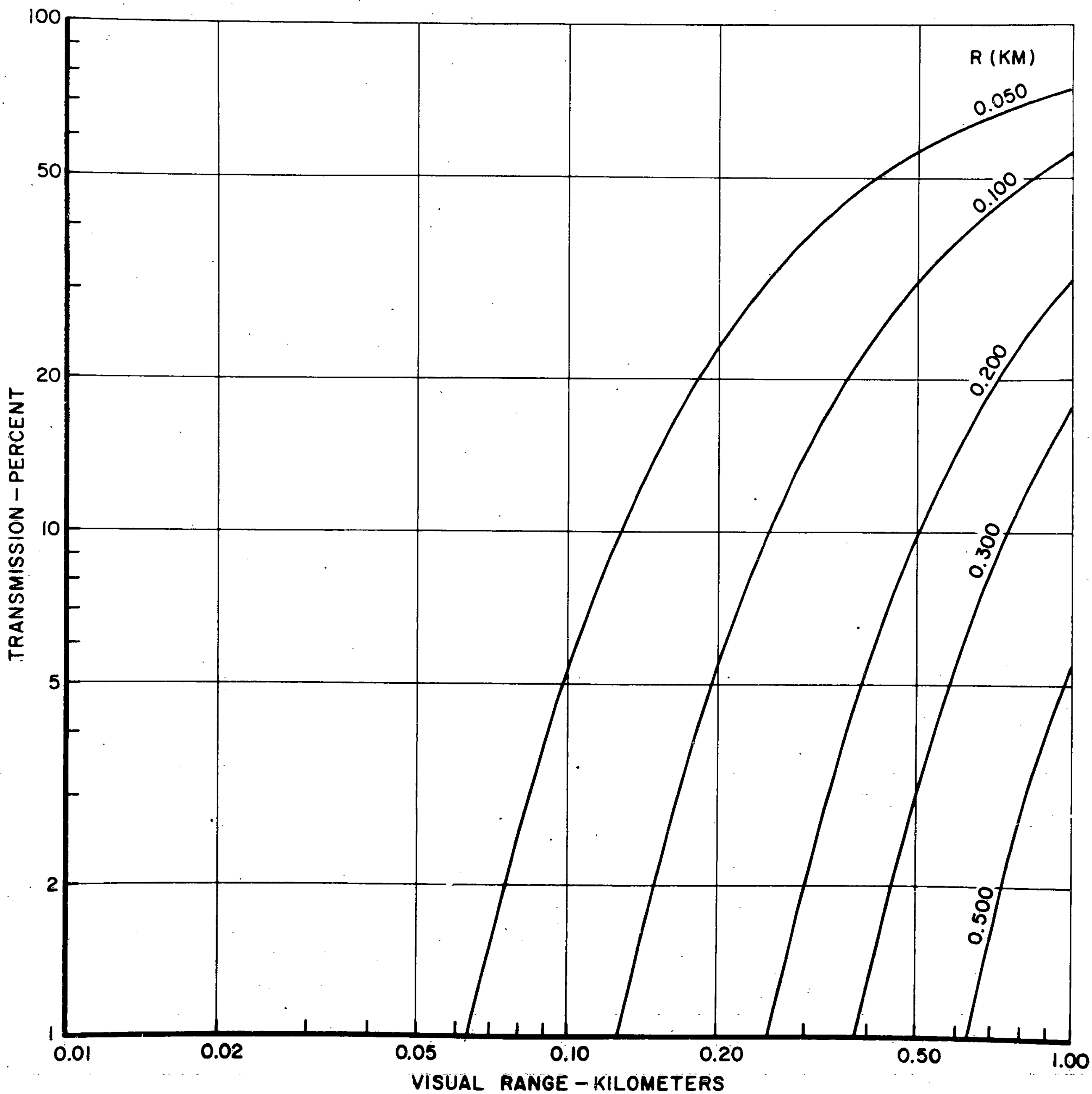
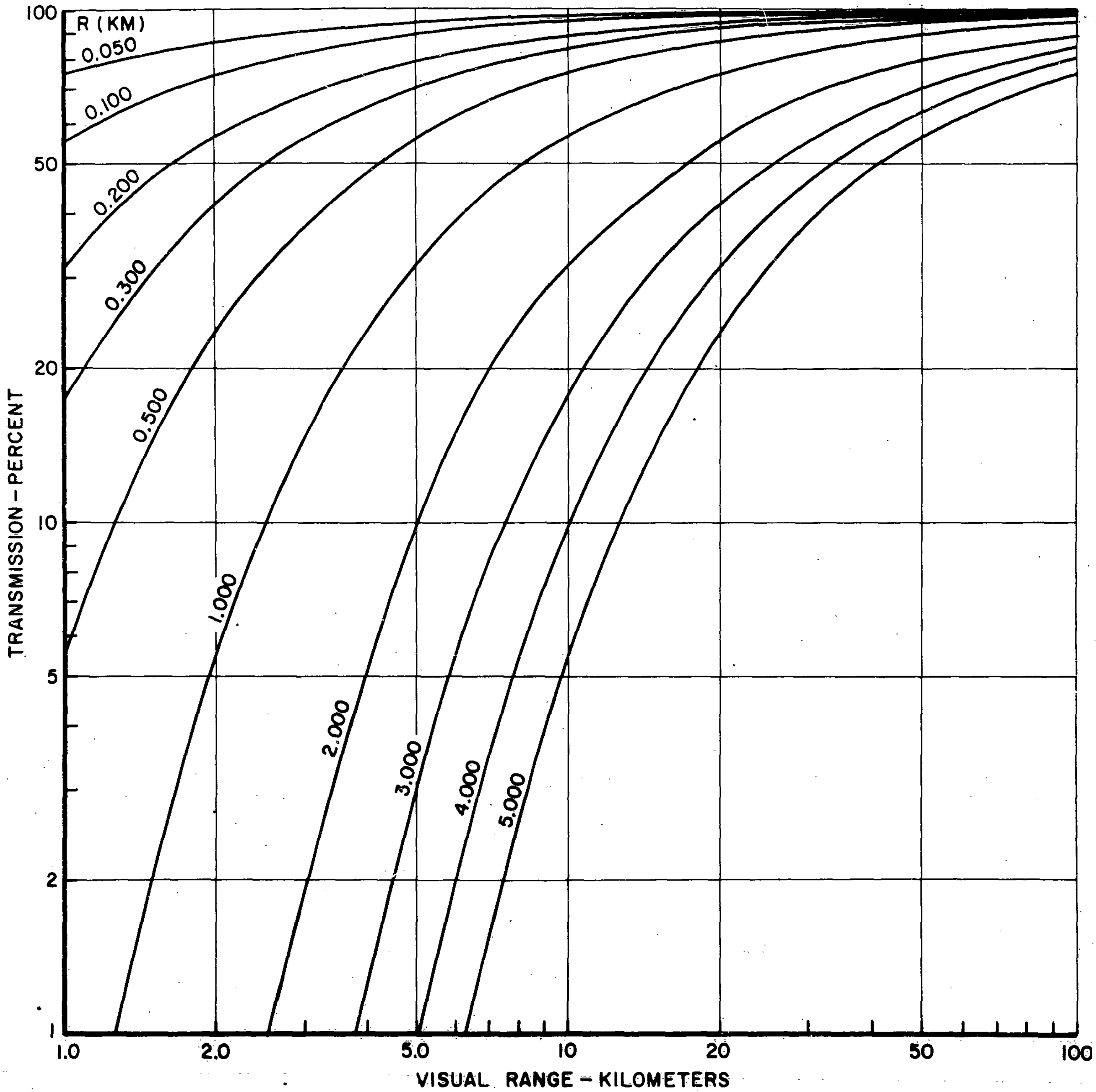


FIG. 26 TRANSMISSION ACROSS THE GIVEN PATH LENGTH BY AN ATMOSPHERE CHARACTERIZED BY THE GIVEN VISUAL RANGE



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ATMOSPHERIC TRANSMISSION OF LIGHT FOR CLEAR AIR AND FOG IN THE SPECTRAL REGION 0.35 TO 1.10 MICRONS

Alan R. Downs

BRL Memorandum Report 1561 April 1964

RDT & E Project No. 1M523801A286

UNCLASSIFIED Report

Light Transmission vs Humidity

Light Transmission - Atmospheric effects

Methods are described for estimating the transmission of light by a clear atmosphere for humidities ranging from 0.1×10^{-6} to 100×10^{-6} g/cm^3 and temperatures between $-40^{\circ}C$ and $+60^{\circ}C$ for path lengths between 1000 and 5000 meters. Also, transmissions are given for varying amounts of fog for path lengths up to 200 meters. The paths used are horizontal and near sea level and wavelength intervals of 0.05 micron are used between wavelengths of 0.35 and 1.10 microns.

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